(2)

High Temperature Superconductivity Space Experiment (HTSSE)

Hybrid HTS/Dielectric Resonator Bandpass Filter

Contract Number: N00014-89-C-2248

Final Report

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Novel filter configurations utilizing dielectric resonators in combination with High Temperature Superconductors (HTS) were successfully developed and flight qualified for the High Temperature Superconductivity Space Experiment (HTSSE). All program goals were met and the developed filters exhibit the best electrical performance (extremely low insertion loss) reported to this date.

The developed dielectric resonator probe technique for measurements of properties of HTS was instrumental to the success of the program, allowing for rapid selection of HTS films for flight filters.

Filters and resonator configurations developed on this problem have the potential for extremely hig Q factors (in the the order of tens of millions) when very low loss, high dielectric constant materials such as sapphire (or similar compounds) are used. Higher power handling and precise tuning of the filters is also possible.

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1.0 INTRODUCTION.

High temperature superconductors hold great potential for the reduction of size, mass, and cost of satellite based microwave components and subsystems while at the same time offering dramatically improved performance. The High Temperature Superconductivity Space Experiment (HTSSE) program has served to accelerate the development of practical HTS based microwave components for space and other applications. This report details the design and performance of the hybrid HTS/dielectric resonator bandpass filters developed by Space Systems/Loral SS/L (formerly Ford Aerospace) for HTSSE.

A typical communication satellite may include well over one hundred bandpass filters in input and output multiplexers and other miscellaneous functions. The performance of these filters is critical and for many parameters may dictate the performance of the overall communication channels. High temperature superconductivity offers the potential to dramatically improve the performance of satellite filters, thereby improving the performance of the overall channel.

Size and mass of satellite filters are also important parameters which can be greatly reduced through HTS realizations. Given the numbers of filters involved on a typical communication satellite, reductions in the size and mass of filters can have a very substantial effect on the launch cost of the satellite.

The current state-of-the-art for satellite filter technology is the use of invar cavity and dielectric loaded cavity filters. Figure 1.0-1 is a photograph of a 6 channel satellite input multiplexer based on dielectric loaded cavity filters and Figure 1.0-2 is a photograph of a 12 channel satellite output multiplexer based on invar cavities.

For the HTSSE program, we selected an approach which is an adaptation of the dielectric loaded cavity filters currently used in satellites. This approach offers a number of advantages over the conventional dielectric loaded cavity including the following.

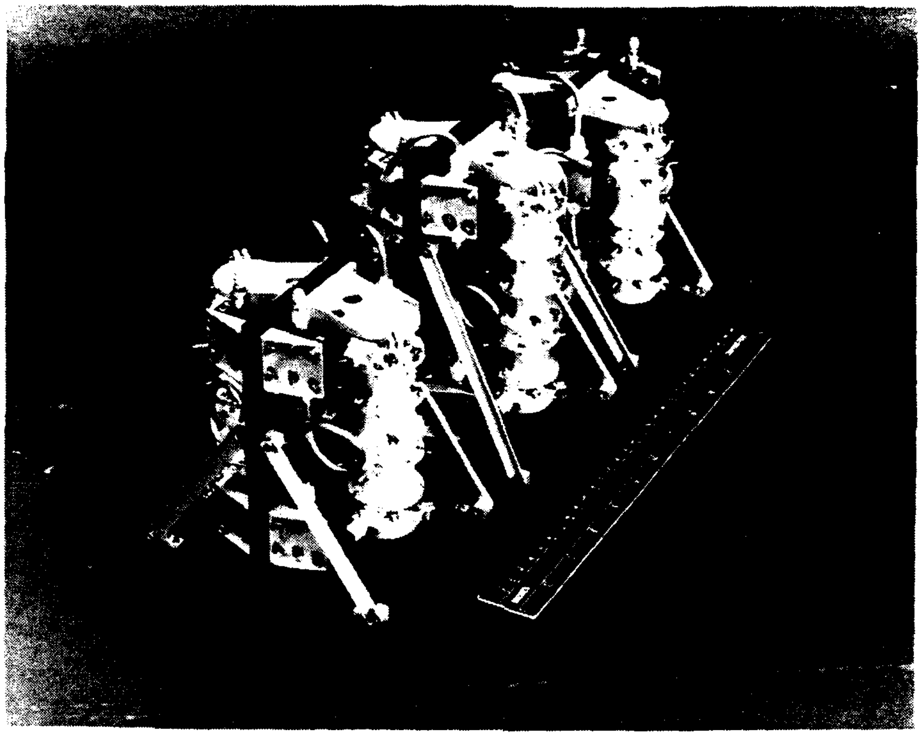


Figure 1.0-1 Photograph of a 6 Channel, Dielectric Loaded Cavity Input Multiplexer for INTLESAT VII. This Photograph Illustrates the Current State-of-the-Art for Satellite Input Multiplexers.

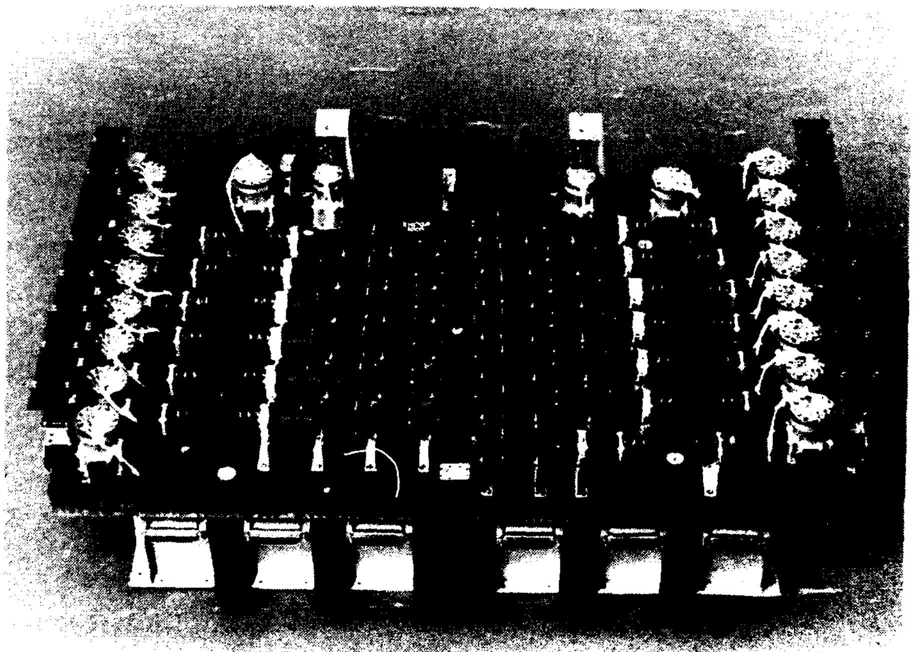


Figure 1.0-2 Photograph of a 12 Channel, Invar Cavity Output Multiplexer for the Superbird Program. This Photograph Illustrates the Current State-of-the-Art for Satellite Output Multiplexers.

- Decreased size and mass

- Dramatic performance improvements as a result of the following effects
  - The resistive losses from the cavity walls are nearly eliminated as a result of the low loss superconductors
  - The dielectric losses associated with the dielectric resonators is at least an order of magnitude lower at cryogenic temperatures.

The hybrid dielectric/superconductor resonator approach also has a number of advantages as compared to planar superconductor filters including the following.

- No patterning of HTS films is required

- Higher filter quality factors (Q) and, hence, higher performance can be achieved

- Either thin film or bulk superconductors can be used. In fact any superconductor can be used making it easy to select whichever material offers the highest performance.

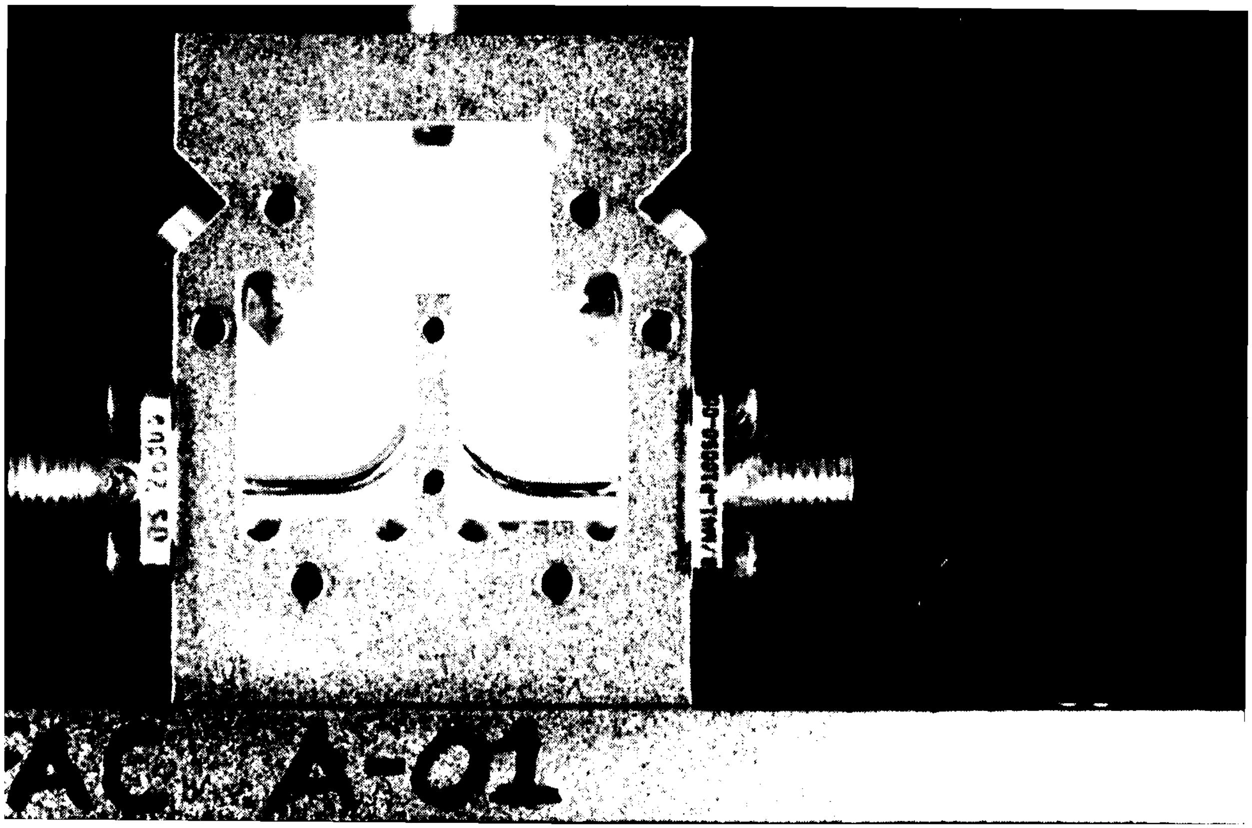
- Higher power handling capability before experiencing performance degradation

- Tunability can be achieved much more easily.

Space Systems/Loral developed two different configurations of hybrid dielectric/HTS resonator filters and delivered five (5) of each type for HTSSE. The resulting filters have performance superior to any other superconducting filter reported to date representing a significant advancement in the development of HTS technology for satellite applications. The two types of filters delivered by Space Systems/Loral for HTSSE are a 3-pole, "full puck" dielectric/HTS resonator filter and a 2-pole, "half cut" dielectric/HTS resonator filter. Figure 1.0-3 shows a photograph of the inside of the full puck filters, and Figure 1.0-4 shows the finished package. Figure 1.0-5 shows the inside of the half cut filters, and Figure 1.0-6 shows the finished package for the half cut filters.

The hybrid dielectric/HTS resonators introduced by SS/L for the HTSSE program can also be used for other microwave applications. For example, in two of the appendices this report, a superconductor surface resistance measurement technique developed by SS/L based on a dielectric/HTS resonator is described. This technique was used to select HTS samples suitable for use on the HTSSE program. The hybrid dielectric/HTS resonator can also be used to make ultra-stable oscillators.

In this report, the design and performance of the dielectric/HTS resonator filters developed for HTSSE are described. In Section 2, the filter operation and design are described. The measured performance of the filters is detailed in Section 3, and the properties of the HTS films used are given in Section 4. Section 5 gives a summary and conclusions.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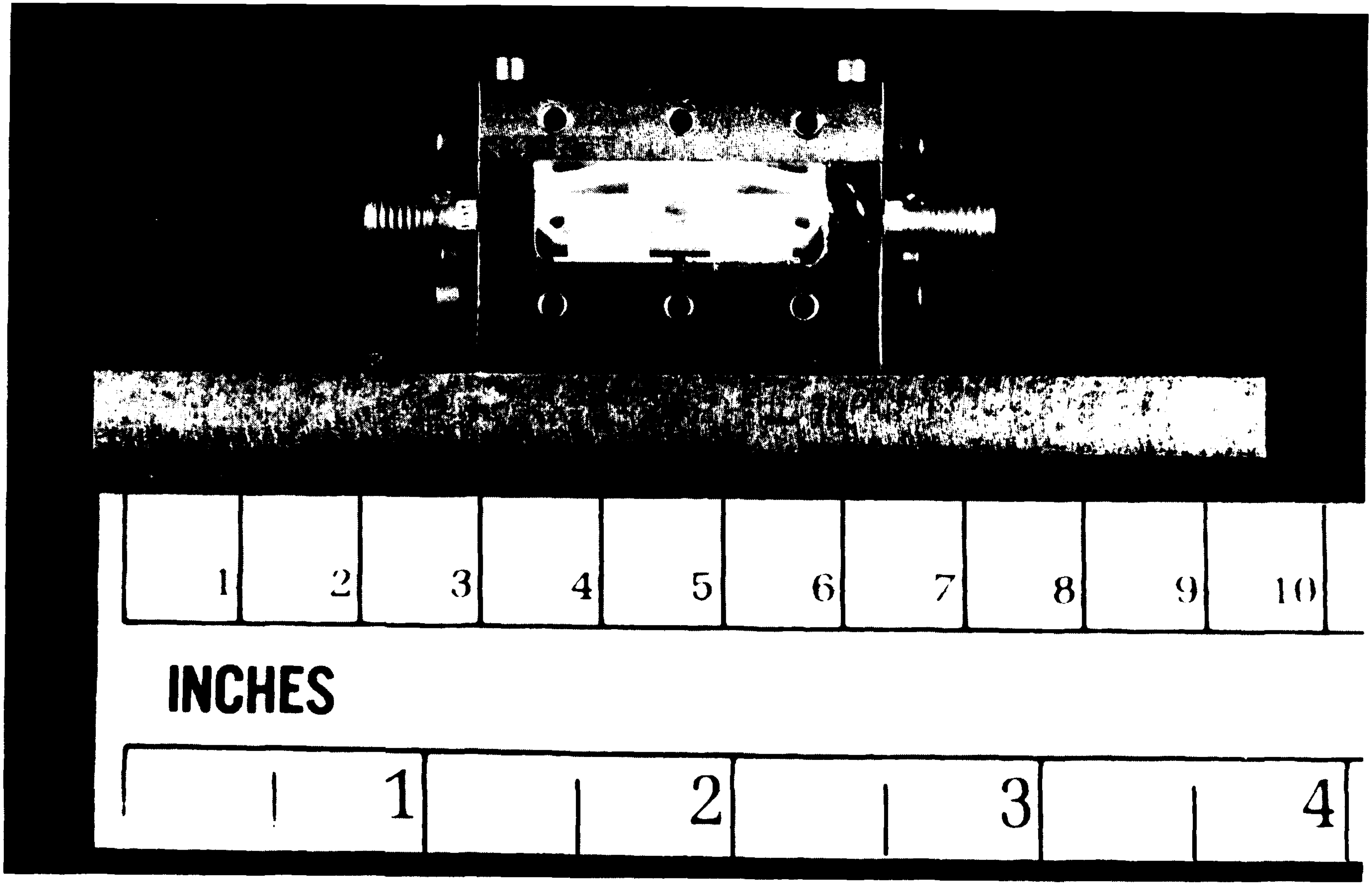

Figure 1.0-5 Internal Photograph of One of the 2-Pole Flight Model Filters Delivered For HTSSE.

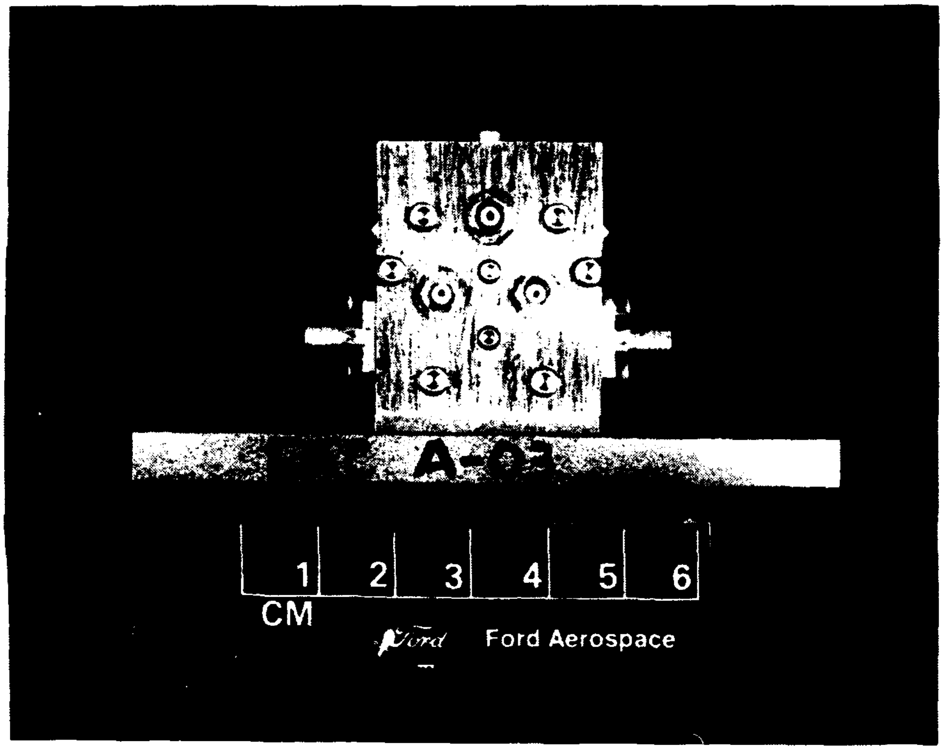

Figure 1.0-4 Photograph of the Finished Package for One of the 3-Pole Flight Model Filters Delivered For HTSSE.

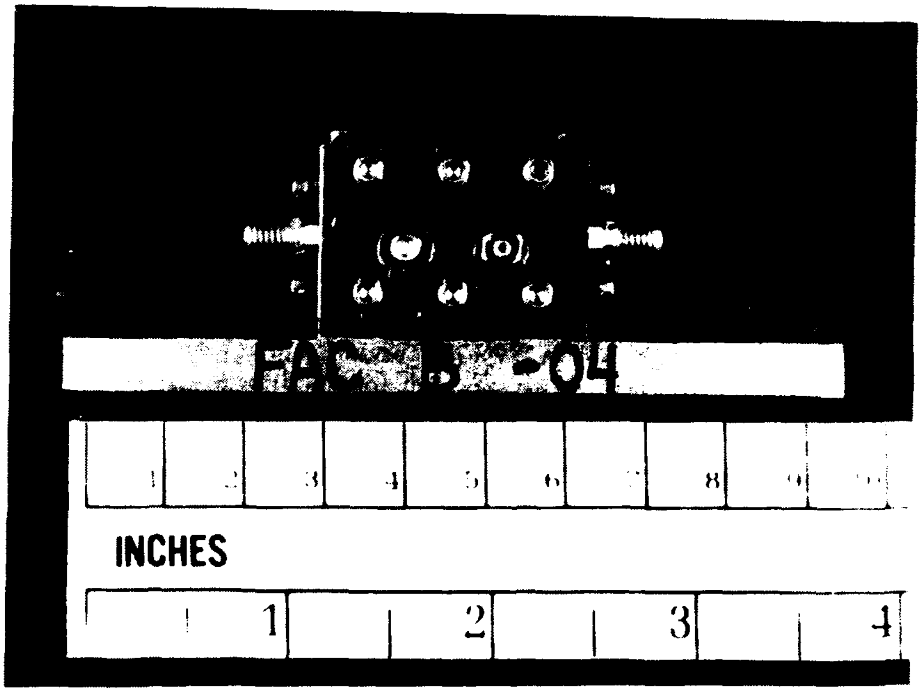

Figure 1.0-6 Photograph of the Finished Package for One of the 2-Pole Flight Model Filters Delivered For HTSSE.

2.0 DESCRIPTION OF DELIVERED DEVICES.

HTS materials promise significant benefits for space communication systems by reducing at least by an order of magnitude the resistive losses of filters, waveguide feeds, and transmission lines. Significant reduction in size and weight of these components is also expected (excluding cryogenics). However, in typical microwave structures utilizing these materials in the form of thin films, HTS compatible dielectric substrates and their dielectric losses are a performance limiting factor. Because of these reasons, for the HTSSE program we proposed a novel concept of using dielectric resonators in conjunction with HTS materials. This hybrid approach offers several advantages: dielectric resonator materials have extremely low losses at cryogenic temperatures, reduced size in comparison to traditional dielectric resonators, exceptional temperature stability, tunability, and versatility (any HTS material can be easily substituted in the realized filter structures).

In the past , a number of different filter configurations based on high dielectric constant , low loss ceramics have been developed [1, 2, 3] . These techniques involved suspending a dielectric resonator inside a waveguide cavity below cutoff. One of the basic advantages of a dielectric resonator as compared to a dielectric filled cavity is the significant reduction of conductive losses affecting the overall Q factor of the structure. Evanescent fields outside of the dielectric resonator practically vanish on a properly designed metal resonator enclosure . Therefore, dielectric losses (loss tangent) dominate and determine the Q factor of the dielectric resonator. However, such a structure is somewhat larger than a same frequency metal wall cavity filled with a similar dielectric. Using traditional metals for partial walls of the dielectric resonator and creating " post " dielectric resonators , quarter, or half cut image resonators results in significant degradation of the Q factor (due to conductive losses in partially metal coated dielectric resonators). Typical modes used and their electromagnetic field distributions are shown in Figure 2.0-1.

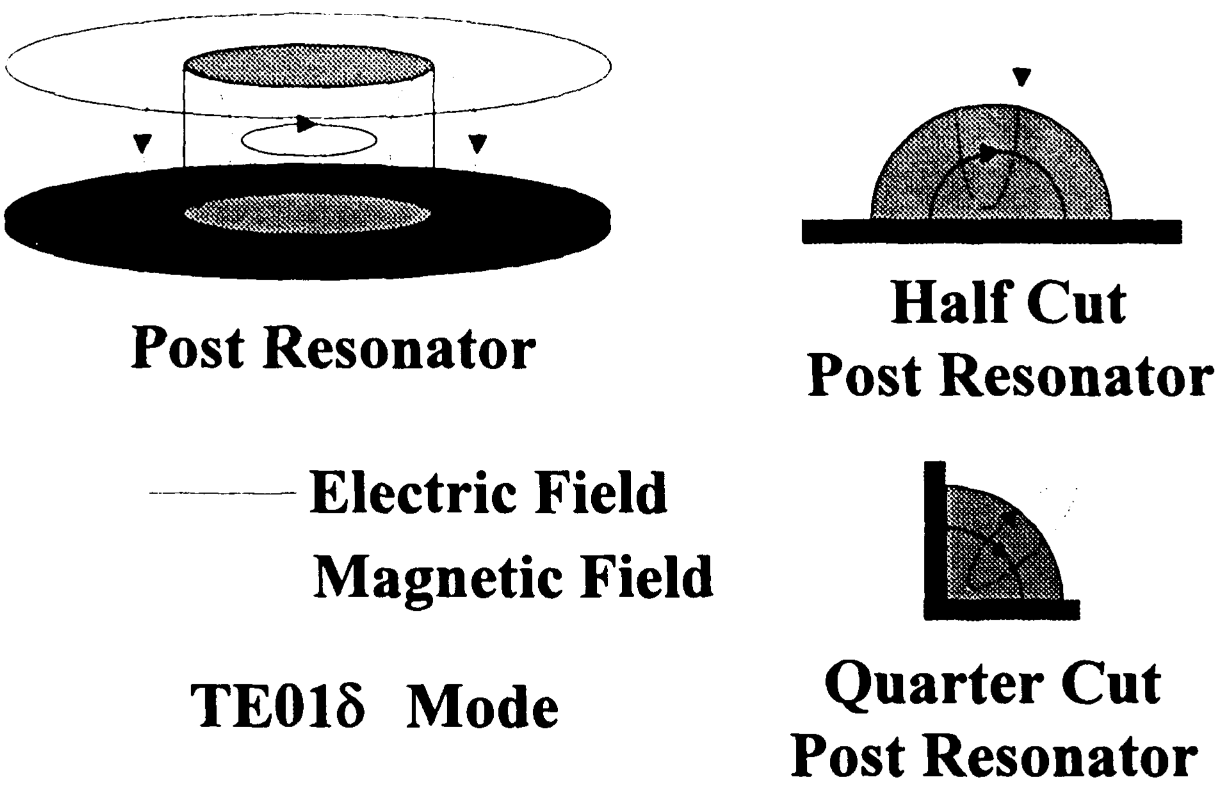

FIGURE 2.0-1 Field Distributions for Various Dielectric Resonator Configurations.

These resonators can be easily designed using published formulas [4,5,6]. Using newly developed HTS materials practically eliminates conductive losses and the excellent dielectric properties (Q factor) of the typical structures are retained. This is a basic idea for hybrid dielectric/HTS resonators. Utilization of these resonators further reduces the size and weight of the filter structures, due to reduced size of the enclosures. Such reductions are very important in size and weight constrained satellite applications (targeted by HTSSE demonstration).

A great deal of research into HTS fabrication has been spent finding suitable substrate materials and developing reliable methods of thin film deposition. Recent developments have produced good films, typically on Lanthanum Aluminate or a related compound. However, these substrate materials seriously degrade device performance due to their relatively high loss tangent. Recently sapphire (single crystal) and temperature stable ceramics from a number of companies have shown exceedingly high Q factor at low temperatures . Figure 2.0-2 shows the Q factor of an ε =25 ceramic over a range of temperatures. Kobayashi [7] has reported that this type of ceramic can achieve Q factors of over 140,000 at 77K and Qs of more than several million are possible using sapphire. This characteristic has been used to measure the quality of HTS films by a dielectric resonator probe method (described in para. 4.2). Virtually eliminating dielectric losses leaves only dissipation due to the finite conductivity of the cavity walls. Either the cavity can be enlarged (limited by waveguide moding) or the metal walls replaced by HTS material . HTS walls are particularly attractive since they can be placed directly in contact with the dielectric with little degradation of performance, producing a highly miniature, extremely high Q resonator. In addition, the HTS substrate itself may be of any material.

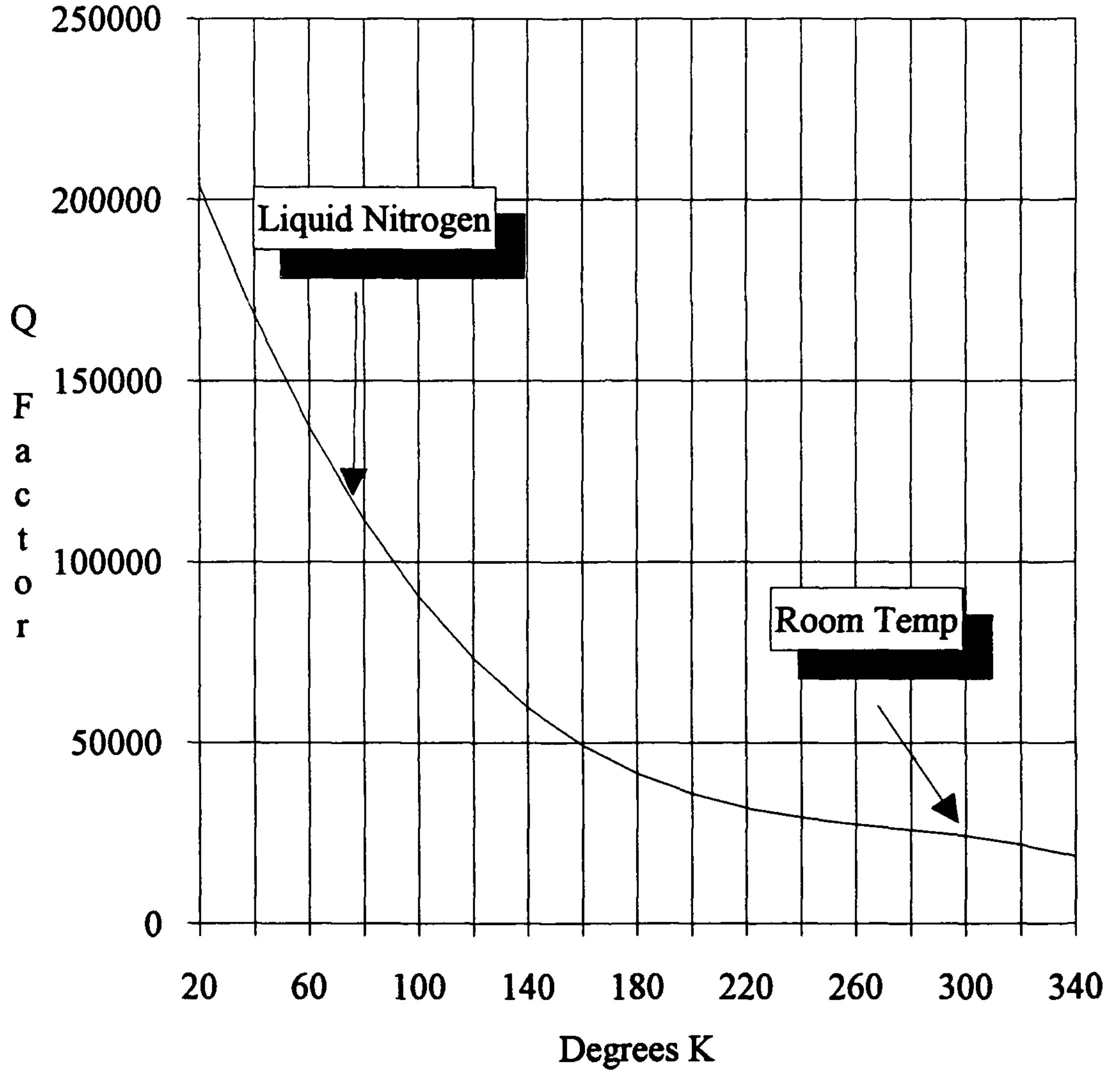

FIGURE 2.0-2 Q Factor of High Dielectric Constant Ceramic.

2.1 3-POLE HTS/DIELECTRIC RESONATOR FILTERS.

Since HTS thin films have been primarily deposited on flat substrates, the filters developed for this program use HTS on the ends of the resonators only. This configuration of the dielectric resonator is called " post " dielectric resonator and is shown in Figure 2.1-1.
The resonant frequency of this structure can be determined in general by using the equations from [6].

$$[F_n(u)+M_n(v)][k_1^2F_n(u)+k_2^2M_n(v)]=n^2h^2\left(\frac{1}{u^2}-\frac{1}{v^2}\right)^2 \tag{1}$$

where

$$F_n(u)=\frac{J_n'(u)}{uJ_n(u)} \qquad M_n(v)=-\frac{H_n^{(2)\prime}(v)}{vH_n^{(2)}(v)} \tag{2}$$

$$u=\frac{D}{2}\sqrt{k_1^2-h^2} \qquad v=\frac{D}{2}\sqrt{k_2^2-h^2} \tag{3}$$

$$k_1=\frac{\omega}{c}\sqrt{\epsilon_r} \qquad k_2=\frac{\omega}{c} \tag{4}$$

$$h=\frac{2\pi}{\lambda_g}=\frac{\pi l}{L}, \qquad l=0,1,2,\cdots \tag{5}$$

For our specific application a fundamental mode TE_{011} was selected. A computer program to calculate the resonant frequency in this case is listed in Figure 2.1-2.

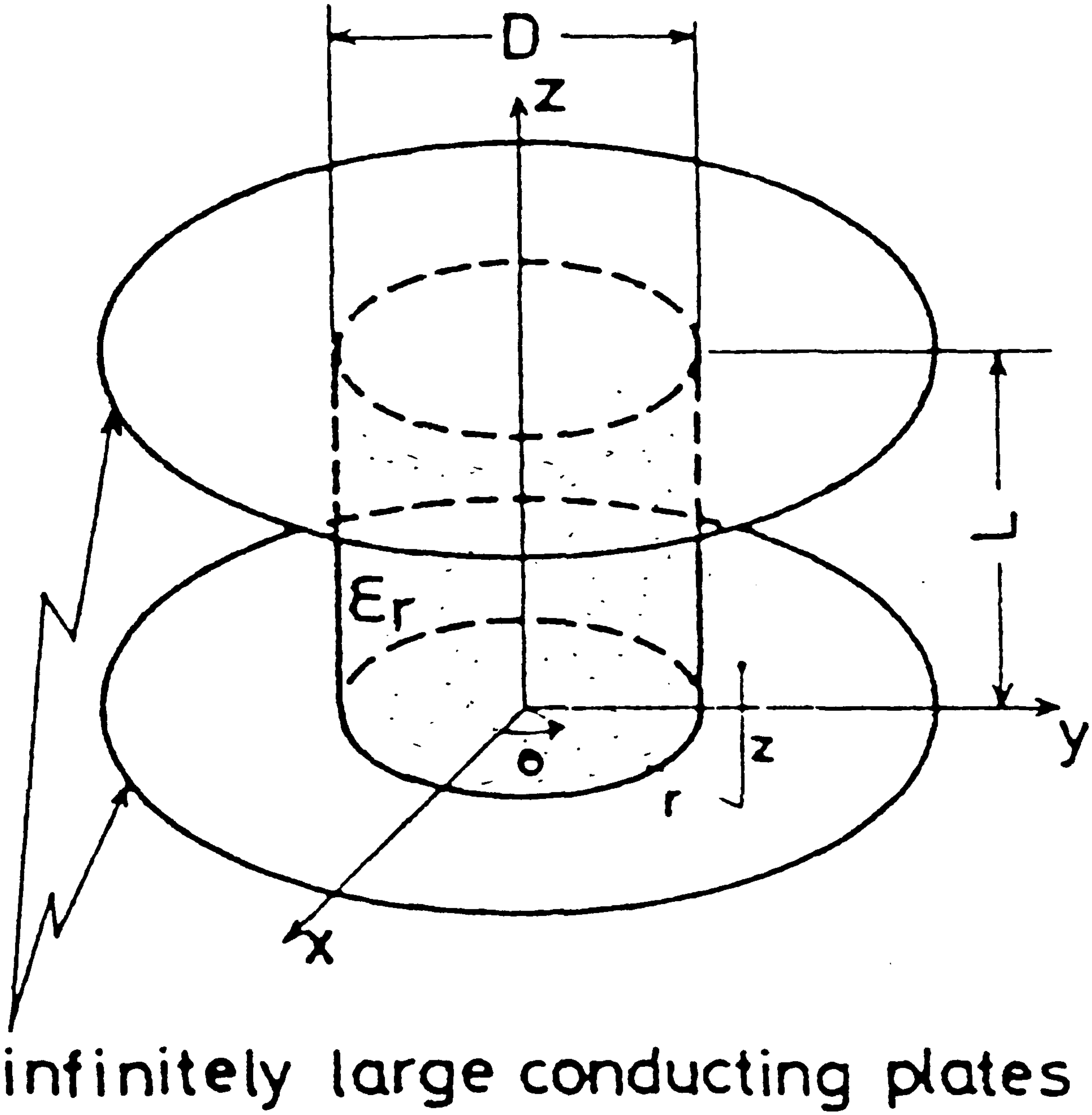

FIGURE 2.1-1 " POST" Dielectric Resonator Configuration- A Cylindrical Dielectric Rod Resonator Placed Between Two Parallel Conducting Plates.

```
10 REM RESONANT FREQUENCY OF DIELECTRIC POST RESONATOR  TEO11 MODE
20 REM BY J.F , DECEMBER 5, 1988
30 DIM F(200),LAMBDA(200),KSI(200),TETA(200),QE(200),J0(200),J1(200)
35 DIM K0(200),K1(200)
40 PRINT " ENTER DIAMETER OF DIELECTRIC RESONATOR-INCHES"
50 INPUT D
60 PRINT "ENTER  THICKNESS OF DIELECTRIC RESONATOR -INCHES"
70 INPUT L
80 PRINT " ENTER DIELECTRIC CONSTANT OF DIELECTRIC RESONATOR"
90 INPUT ER
100 PIE=3.1415927
110 RO11=3.832
120 SUM=(PIE*D*.5/L)**2
130 FONORM=RO11**2*(1-1/SQR(RO11**2+SUM))**2+SUM
140 LAMBDASQ=ER*(PIE*D)**2/FONORM
150 LAMBDA=SQR(LAMBDASQ)
160 FO=11802.874/LAMBDA
170 PRINT " RESONANT FREQUENCY OF POST DIELECTRIC RESONATOR"
180 PRINT "                  TE011 MODE"
190 PRINT USING " DIAMETER OF DIELECTRIC RESONATOR=##.### INCHES",D
200 PRINT USING " LENGTH OF DIELECTRIC RESONATOR=##.###INCHES",L
210 PRINT USING " DIELECTRIC CONSTANT OF DIELECTRIC RESONATOR=###.##",ER
220 PRINT USING " APPROXIMATE RESONANT FREQUENCY=#######.## MHZ",FO
230 F(1)=FO -50
240 F(2)=FO-100
250 I=1
260 LAMBDA(I)=11802.874/F(I)
270 KSI(I)=(SQR(ER*(2*PIE/LAMBDA(I))**2-(PIE/L)**2))*D/2
280 TETA(I)=SQR((PIE/L)**2-(2*PIE/LAMBDA(I))**2)*D/2
290 J0(I)=FN.J0(KSI(I))
300 J1(I)=FN.J1(KSI(I))
310 K0(I)=FN.K0(TETA(I))
320 K1(I)=FN.K1(TETA(I))
330 QE(I)=(J0(I)*KSI(I))/J1(I)+(K0(I)*TETA(I))/K1(I)
340 I=I+1
350 IF I<=2 THEN GOTO 260
360 PR=QE(I-2)-QE(I-1)
370 F(I)=F(I-1)*QE(I-2)/PR-F(I-2)*QE(I-1)/PR
371 LAMB=11802.874/F(I)
375 PRINT USING  "FREQUENCY=#######.## MHZ",F(I)
380 IF ABS(QE(I-1))>=.00001 THEN GOTO 260
390 PRINT USING " EQUATION ZERO=##.##########",QE(I-1)
400 PRINT USING " RESONANT FREQUENCY=#######.## MHZ",F(I)
410 PRINT USING " KSI VARIABLE=##.######",KSI(I-1)
420 PRINT USING " TETA VARIABLE=##.#####",TETA(I-1)
421 LOSS1=J0(I-1)**2-(2/KSI(I-1))*J0(I-1)*J1(I-1)+J1(I-1)**2
422 FUDGE=J1(I-1)**2/K0(I-1)**2
423 LOSS2=K0(I-1)**2+(2/TETA(I-1))*K1(I-1)*K0(I-1)-K1(I-1)**2
424 LOSS3=FUDGE*LOSS2
425 DRATIO=LOSS3/LOSS1
426 PRINT USING " DISSIPATION RATIO=##.######",DRATIO
427 ACON=1+DRATIO/ER
428 BCON=(LAMB/(2*L))**3*(1+DRATIO)/(60*PIE*PIE*ER)
429 PRINT USING "ACONSTANT=####.#####",ACON
430 PRINT USING "BCONSTANT=####.####",BCON
431 DEF FN.J0(Y)
440 IF Y>=3 THEN GOTO 500
450 Y1=Y/3
460 Y2=1-2.2499997*Y1**2+1.2656208*Y1**4-.3163866*Y1**6
470 Y3=Y2+.0444479*Y1**8-.0039444*Y1**10+.00021*Y1**12
480 FN.J0=Y3
490 GOTO 580
500 Y1=3/Y
510 Y2= .79788456-.00000077*Y1-.0055274*Y1**2-.00009512*Y1**3
520 Y3= Y2+.00137237*Y1**4-.00072805*Y1**5+.00014476*Y1**6
530 Y4=Y-.78539816-.04166397*Y1-.00003954*Y1**2+.00262573*Y1**3
```

FIGURE 2.1-2 A Computer Program to Calculate the Resonant Frequency of the " Post" Dielectric Resonator.

```
540 Y5=Y4-.00054125*Y1**4-.00029333*Y1**5+.0001358*Y1**6
550 Y6=Y3/SQR(Y)
560 Y7=Y6*COS(Y5)
570 FN.J0=Y7
580 FNEND
590 DEF FN.J1(Y)
600 IF Y>=3 THEN GOTO 670
610 Y1=Y/3
620 Y2=.5 -.56249985*Y1**2+.21093573*Y1**4-.03954289*Y1**6
630 Y3=Y2+.00443319*Y1**8-.00031761*Y1**10+.00001109*Y1**12
640 Y3=Y3*Y
650 FN.J1=Y3
660 GOTO 750
670 Y1=3/Y
680 Y2= .79788456+.00000156*Y1+.01659667*Y1**2+.00017105*Y1**3
690 Y3= Y2-.00249511*Y1**4+.00113653*Y1**5-.00020033*Y1**6
700 Y4= Y-2.35619449+.12499612*Y1+.0000565*Y1**2-.0063789*Y1**3
710 Y4= Y4+.00074348*Y1**4+.000779824*Y1**5-.00029166*Y1**6
720 Y5=Y3/SQR(Y)
730 Y6=Y5*COS(Y4)
740 FN.J1=Y6
750 FNEND
760 DEF FN.I0(Y)
770 IF Y>=3.75 THEN GOTO 830
780 Y1=Y/3.75
790 Y2=1+3.5156229*Y1**2+3.0899424*Y1**4+1.2067492*Y1**6+.2659732*Y1**8
800 Y2=Y2+.0360768*Y1**10+.0045813*Y1**12
810 FN.I0=Y2
820 GOTO 890
830 Y1=3.75/Y
840 Y2=.39894228 +.01328592*Y1+.00225319*Y1**2-.00157565*Y1**3
850 Y2=Y2+.00916281*Y1**4-.02057706*Y1**5+.026355537*Y1**6
860 Y2=Y2-.01647633*Y1**7+.00392377*Y1**8
870 Y2=Y2*EXP(Y)/SQR(Y)
880 FN.I0=Y2
890 FNEND
900 DEF FN.I1(Y)
910 IF Y>=3.75 THEN GOTO 980
920 Y1=Y/3.75
930 Y2=.5 +.87890594*Y1**2+.51498869*Y1**4+.15084934*Y1**6+.02658733*Y1**8
940 Y2=Y2+.00301532*Y1**10+.00032411*Y1**12
950 Y2=Y2*Y
960 FN.I1=Y2
970 GOTO 1040
980 Y1=3.75/Y
990 Y2=.39894228-.03988024*Y1-.00362018*Y1**2+.00163801*Y1**3
1000 Y2=Y2-.01031555*Y1**4+.02282967*Y1**5-.02895312*Y1**6
1010 Y2=Y2+.01787654*Y1**7-.004420059*Y1**8
1020 Y2=Y2*EXP(Y)/SQR(Y)
1030 FN.I1=Y2
1040 FNEND
1050 DEF FN.K0(Y)
1060 IF Y>=2 THEN GOTO 1140
1070 Y1=Y/2
1080 Y2=FN.I0(Y)
1090 Y3=-LOG(Y1)*Y2
1100 Y3=Y3-.57721566+.4227842*Y1**2+.23069756*Y1**4+.0348859*Y1**6
1110 Y3=Y3+.00262698*Y1**8+.0001075*Y1**10+.0000074*Y1**12
1120 FN.K0=Y3
1130 GOTO 1190
1140 Y1=2/Y
1150 Y2=1.25331414-.07832358*Y1+.02189568*Y1**2-.01062446*Y1**3
1160 Y2=Y2+.00587872*Y1**4-.0025154*Y1**5+.00053208*Y1**6
1170 Y3=Y2/(SQR(Y)*EXP(Y))
1180 FN.K0=Y3
1190 FNEND
```

```
1200 DEF FN.K1(Y)
1210 IF Y>=2 THEN GOTO 1300
1220 Y1=Y/2
1230 Y2=FN.I1(Y)
1240 Y3=Y*Y2*LOG(Y1)
1250 Y3=Y3+1+.15443144*Y1**2-.67278579*Y1**4-.18156897*Y1**6-.01919402*Y1**8
1260 Y3=Y3-.00110404*Y1**10-.00004686*Y1**12
1270 Y3=Y3/Y
1280 FN.K1=Y3
1290 GOTO  1350
1300 Y1=2/Y
1310 Y2=1.25331414+.23498619*Y1-.0365562*Y1**2+.01504268*Y1**3
1320 Y2=Y2-.00780353*Y1**4+.00325614*Y1**5-.00068245*Y1**6
1330 Y2=Y2/(SQR(Y)*EXP(Y))
1340 FN.K1=Y2
1350 FNEND
1360 END
```

```
 ENTER DIAMETER OF DIELECTRIC RESONATOR-INCHES
? .3
ENTER  THICKNESS OF DIELECTRIC RESONATOR -INCHES
? .18
 ENTER DIELECTRIC CONSTANT OF DIELECTRIC RESONATOR
? 25
 RESONANT FREQUENCY OF POST DIELECTRIC RESONATOR
              TE011 MODE
 DIAMETER OF DIELECTRIC RESONATOR= 0.300 INCHES
 LENGTH OF DIELECTRIC RESONATOR= 0.180INCHES
 DIELECTRIC CONSTANT OF DIELECTRIC RESONATOR= 25.00
 APPROXIMATE RESONANT FREQUENCY=    9984.64 MHZ
FREQUENCY=    9911.82 MHZ
FREQUENCY=    9912.15 MHZ
FREQUENCY=    9912.14 MHZ
FREQUENCY=    9912.14 MHZ
 EQUATION ZERO= 0.00000524521
 RESONANT FREQUENCY=    9912.14 MHZ
 KSI VARIABLE= 2.967810
 TETA VARIABLE= 2.49548
 DISSIPATION RATIO= 0.274985
ACONSTANT=    1.01100
BCONSTANT=    0.0031
Ready
```

The ceramic material used in this application was manufactured by Murata Mfg. Co. and its properties are listed in Figure 2.1-3.

A second step in filter design is typically the calculation of coupling coefficients betweeen individual resonators required to realize specific filter response.
The coupling coefficient between two post resonators can be calculated using formulas derived by Cohn [8].

The basic filter configuration is shown in Figure 2.1-4.

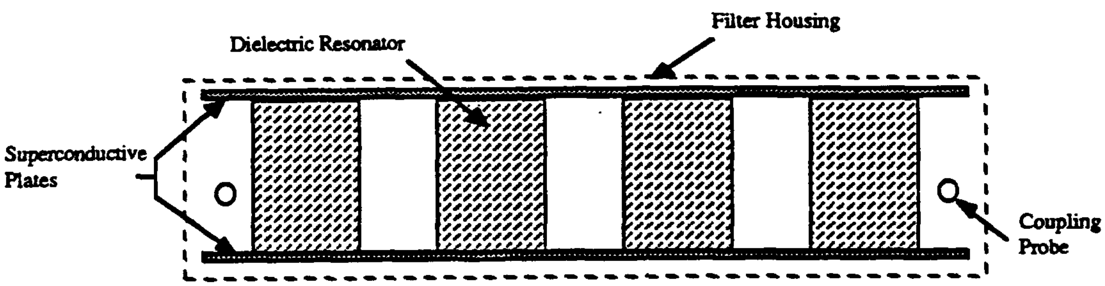

FIGURE 2.1-4 The " Post" Dielectric Resonator Filter Configuration

Several filters were designed, fabricated and tested to verify this concept. Initially, copper and bulk HTS (YBCO) plates were used.
Some of the results are shown in Figures 2.1.-5 and 2.1-6.
A photograph of the BB filter is shown in Figure 2.1-7.
These results were used to design and produce flight filters for HTSSE program.

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* HIGH DIELECTRIC CONSTANT: k=24
* TEMPERATURE COMPENSATION: SELECTABLE FROM 0 TO +6 ppm/°C

TEMPERATURE COEFFICIENT AND DIELECTRIC CONSTANT

CODE	TEMP. COEFF. (ppm/°C)	DIEL. CONST. (+/- 0.5)
C	0	24.2
D	2	24.4
E	4	24.7
F	6	24.9

DRD DIMENSIONS AND FREQUENCY RANGE

PART NUMBER	Dr +/- 0.05 (mm)	Lr +/- 0.05 (mm)	FREQUENCY RANGE (GHz)
DRD022E-010	2.18	0.97	29.77 TO 32.47
DRD024E-011	2.37	1.06	27.38 TO 29.77
DRD026E-012	2.58	1.15	25.15 TO 27.38
DRD028E-013	2.80	1.26	23.17 TO 25.15
DRD031E-014	3.05	1.36	21.27 TO 23.17
DRD033E-015	3.33	1.49	19.48 TO 21.27
DRD036E-016	3.62	1.62	17.93 TO 19.48
DRD039E-018	3.94	1.76	16.47 TO 17.93
DRD043E-019	4.28	1.91	15.16 TO 16.47
DRD046E-020	4.65	2.00	13.95 TO 15.16
DRD051E-022	5.06	2.24	12.82 TO 13.95
DRD055E-024	5.50	2.44	11.80 TO 12.82
DRD060E-027	5.98	2.65	10.85 TO 11.80
DRD065E-029	6.50	2.98	9.98 TO 10.85
DRD071E-031	7.07	3.14	9.18 TO 9.98
DRD077E-034	7.69	3.41	8.44 TO 9.18

TEMPERATURE COEFFICIENT TOLERENCE

SPECIAL CODE	T. COEFF. TOL. (ppm/°C)
----	+/- 2
A	+/- 1

DRT DIMENSIONS AND FREQUENCY RANGE

PART NUMBER	Dr +/- 0.05 (mm)	dr +/- 0.1 (mm)	Lr +/- 0.05 (mm)	FREQUENCY RANGE (GHz)
DRT051E020-022	5.06	2.0	2.24	12.82 TO 13.94
DRT055E020-024	5.50	2.0	2.44	11.80 TO 12.81
DRT060E020-027	5.98	2.0	2.65	10.35 TO 11.79
DRT065E020-029	6.50	2.0	2.88	9.96 TO 10.84
DRT071E020-031	7.07	2.0	3.14	9.18 TO 9.97
DRT077E020-034	7.69	2.0	3.41	8.44 TO 9.17

FIGURE 2.1-3 Properties of Flight Qualified Ceramic Material- E type Resomics Manufactured by Murata Inc.

MATERIAL CHARACTERISTICS

	E MATERIAL	M MATERIAL	K MATERIAL
DIELECTRIC CONSTANT	25	38	89
TEMP. COEFF. (ppm/°C)	0 TO +6	0 TO +6	0 TO +6
Q (1/tan delta) min.	20000 (10GHz)	8000 (7GHz)	5000
INSULATION RESISTANCE (Ohm-cm)	>10^14	>10^13	10^13
EXPANSION COEFFICIENT (ppm/°C)	10.7	6 TO 7	9.5
THERMAL CONDUCTIVITY (cal/cm*sec*°C)	0.0077	0.0046	0.0039
SPECIFIC HEAT (cal/g*°C)	0.0765	0.15	0.13
DENSITY (g/cubic cm)	7.5	5.0	5.7
WATER ABSORPTION (%)	<0.01	<0.01	<0.01
BEND STRENGTH (kg/sq. cm)	1200	1000	1500

Q VALUE

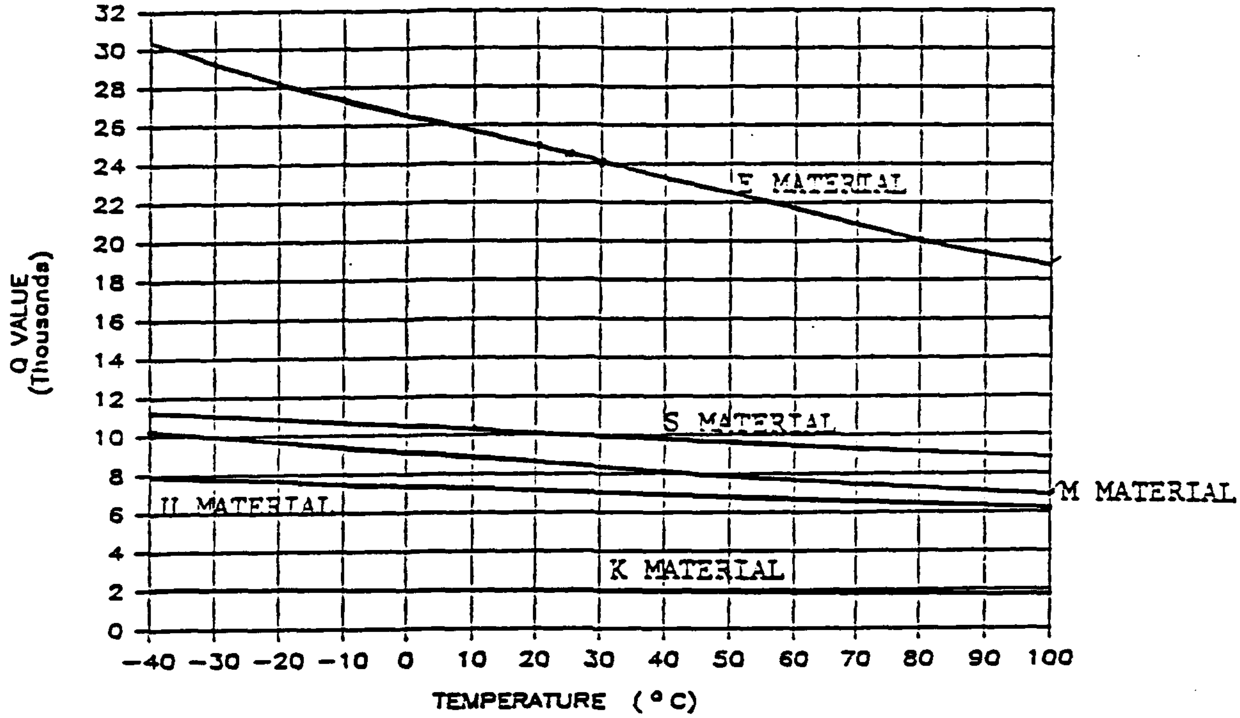
	E MATERIAL	M MATERIAL	K MATERIAL
Q	> 100000/(0.5 * fo)	> 100000/(1.5 * fo +2.0)	> 10000/(1.6 * fo + 1.0)

DIMENSIONAL EQUATIONS

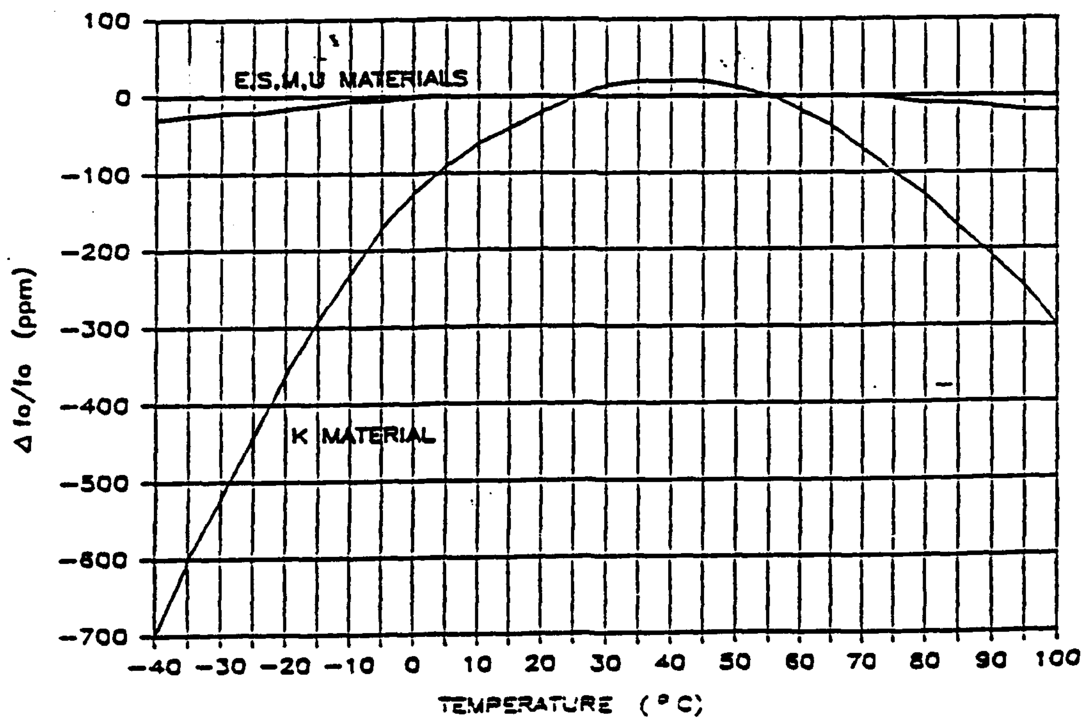
		fo * Dr * k^1/2	
MATERIAL	k	Lr/Dr =0.44	Lr/Dr = 0.32
E	24	322	354
M	38	325	357
K	88	327	339

NOTES: 1.) Lo/Do = 0.44
2.) Do/Dr = 3.0
3.) Lo, Do AND Lr, Dr IN MILLIMETERS
4.) fo IN GHz
5.) FIND STANDARD PART NUMBER DIMENSIONS FOR FIRST APPROXIMATION.
6.) THE FORMULA IS QUITE ACCURATE WHEN SUPPORT HEIGHT EQUALS THE RESONATOR THICKNESS.

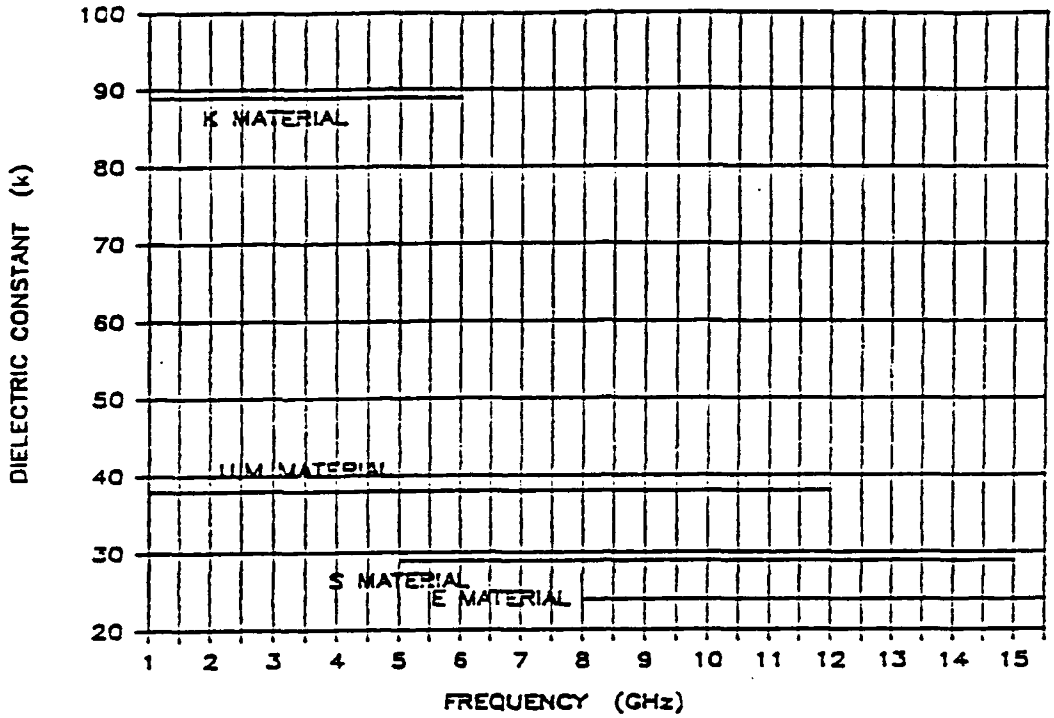
Q vs. TEMPERATURE



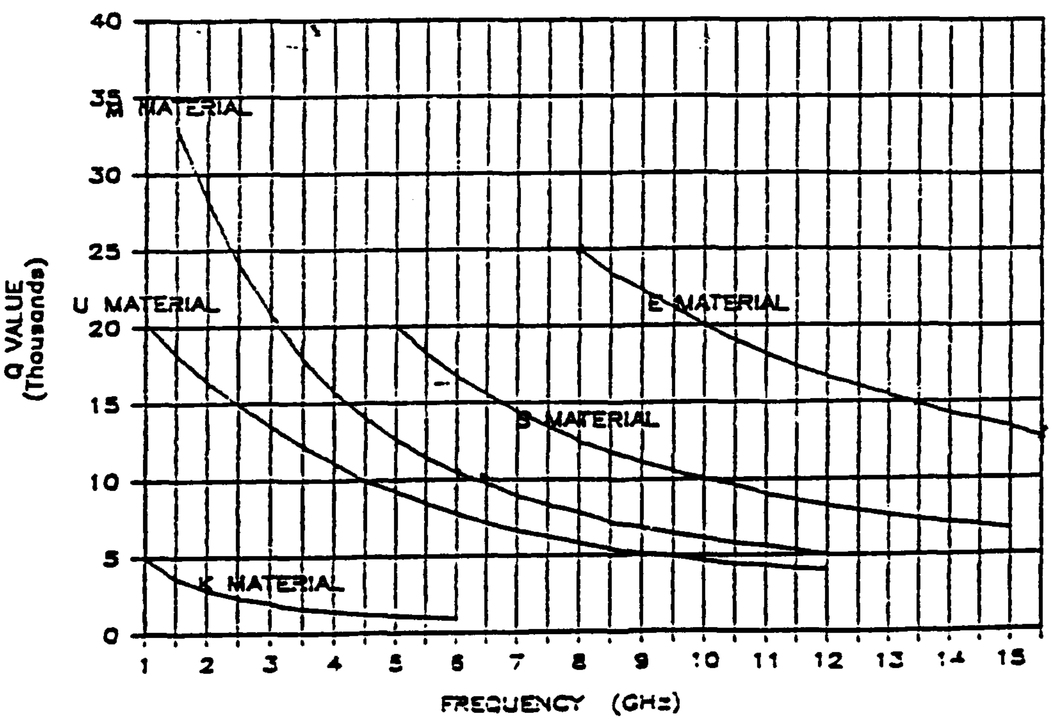
Fo vs. TEMPERATURE



DIELECTRIC CONSTANT vs. FREQUENCY



Q vs. FREQUENCY



300K

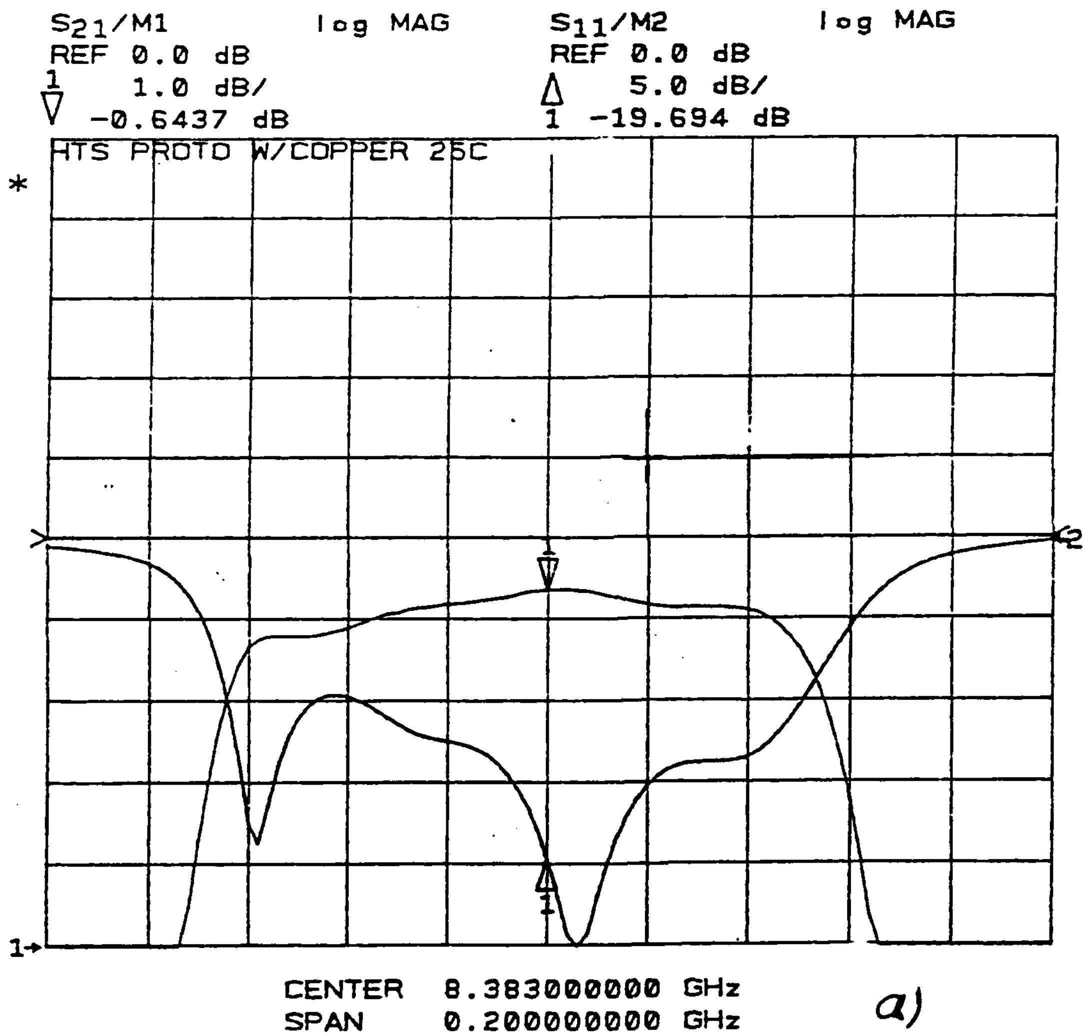


FIGURE 2.1-5 Performance of BB " Post" Dielectric Resonator Filter with Copper Endplates
a) at 300 K
b) at 77 K

77K

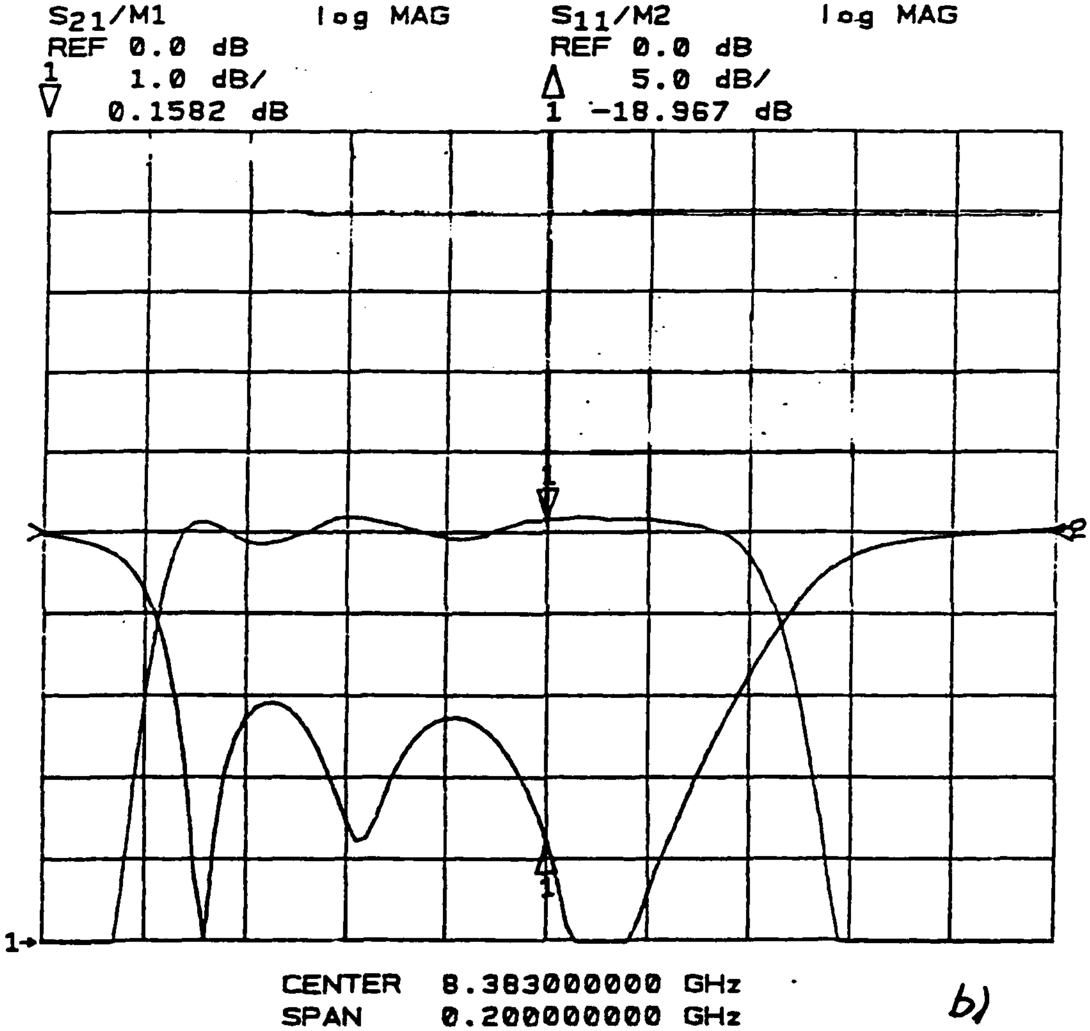


FIGURE 2.1-5 Performance of BB " Post" Dielectric Resonator Filter with Copper Endplates
a) at 300 K
b) at 77 K

300K

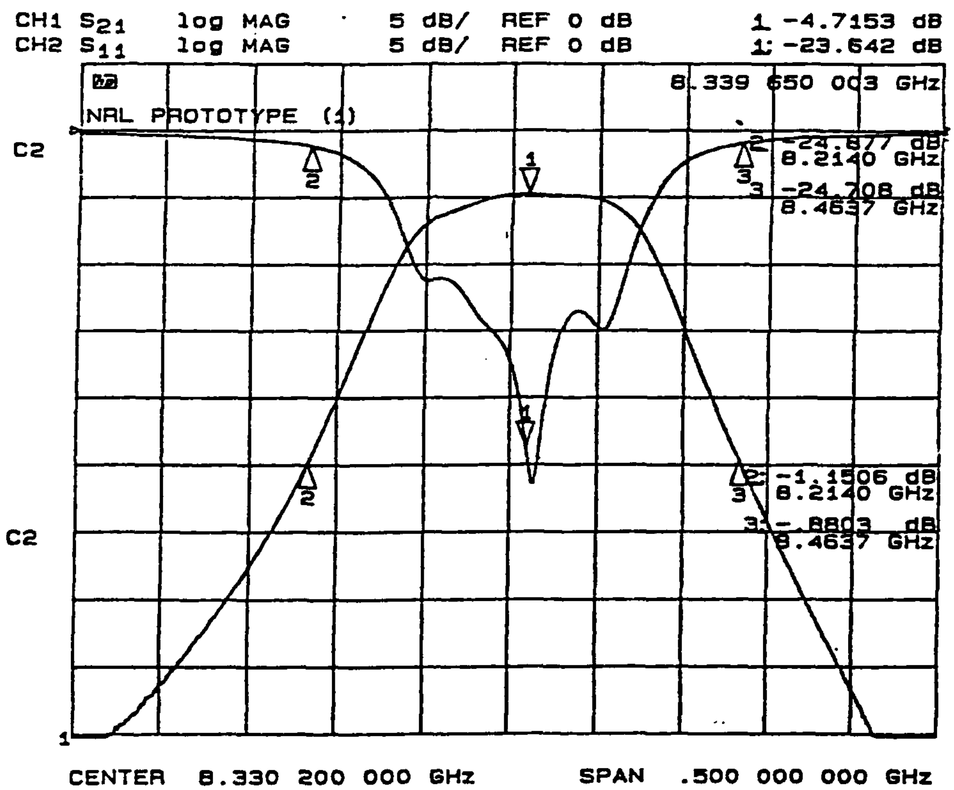


FIGURE 2.1-6 Performance of BB " Post" Dielectric Resonator Filter with Bulk YBCO Endplates.
a) at 300 K
b) at 77 K

77K

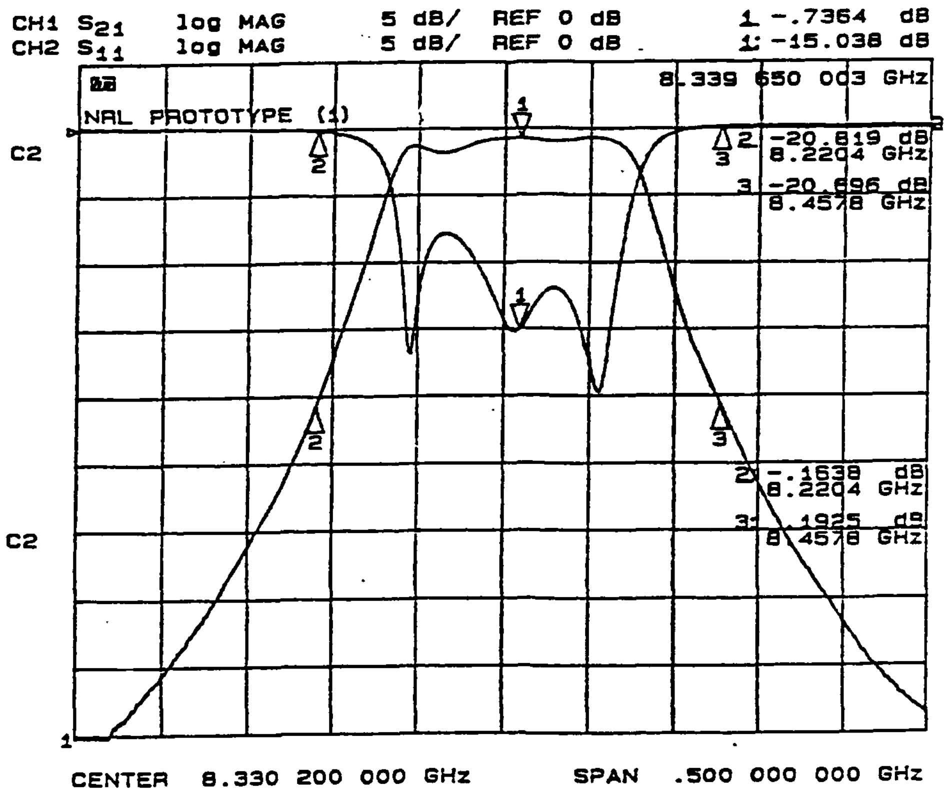


FIGURE 2.1-6 Performance of BB " Post" Dielectric Resonator Filter with Bulk YBCO Endplates.
a) at 300 K
b) at 77 K

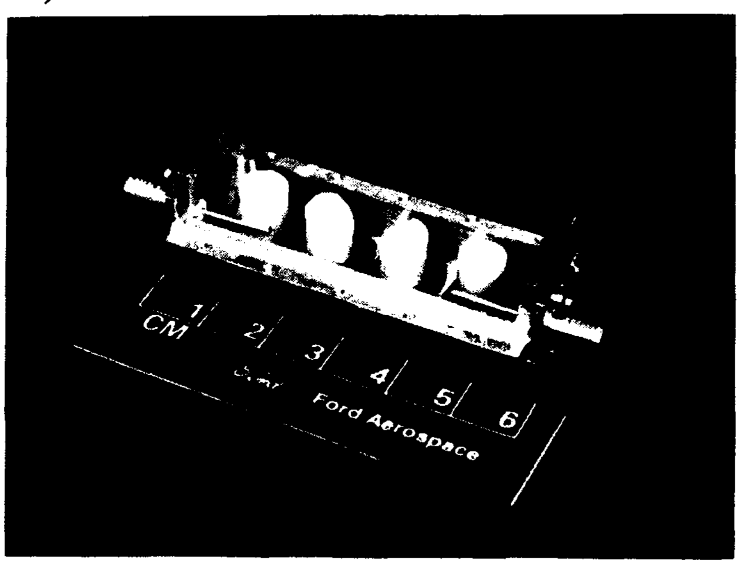


FIGURE 2.1-7 BB " Post" Dielectric Resonator Filter(4-pole).

2.2 2-POLE HALF-CUT HTS/DIELECTRIC RESONATOR FILTERS.

The $TE_{01\delta}$ mode in a circular cylindrical dielectric resonator has a single electric field component (Figure 2.2-1).

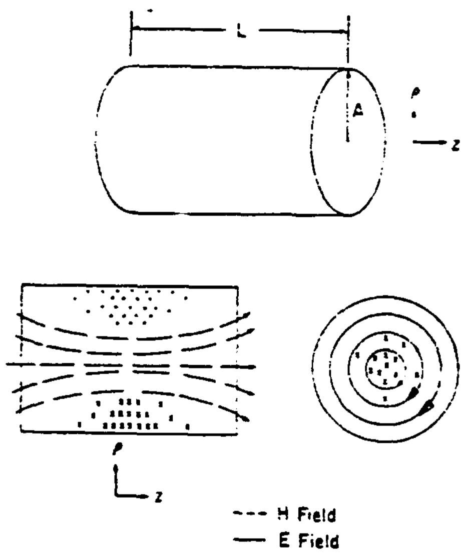


FIGURE 2.2-1 Electromagnetic Field Distribution for the $TE_{01\delta}$ Mode in Dielectric Resonator.

Perfectly conducting radial planes at some radial dimensions have no effect on this mode. This property is utilized in the second configuration of filters for the HTSSE program. By positioning the perfectly conducting plane at $\Phi=180$ degrees we obtain a so called half-cut dielectric resonator
(Figure 2.2-2).

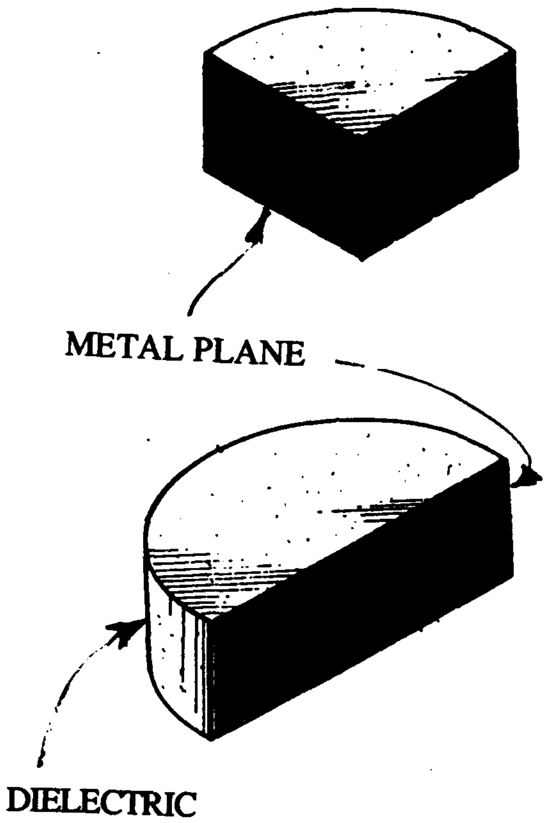


FIGURE 2.2-2 Sectorial : Quarter-Cut and Half-Cut (Image) Dielectric Resonators.

Such a resonator supports a resonant $TE_{01\delta}$ mode at the same frequency as its full circle counterpart with the same radius and length.
Initially several filters were designed, fabricated, and tested using this concept. Copper and bulk HTS materials were used in the development effort. Some of the obtained results are shown in Figures 2.2-3 through 2.2-6. A photograph of the BB filter is shown in Figure 2.2-7.

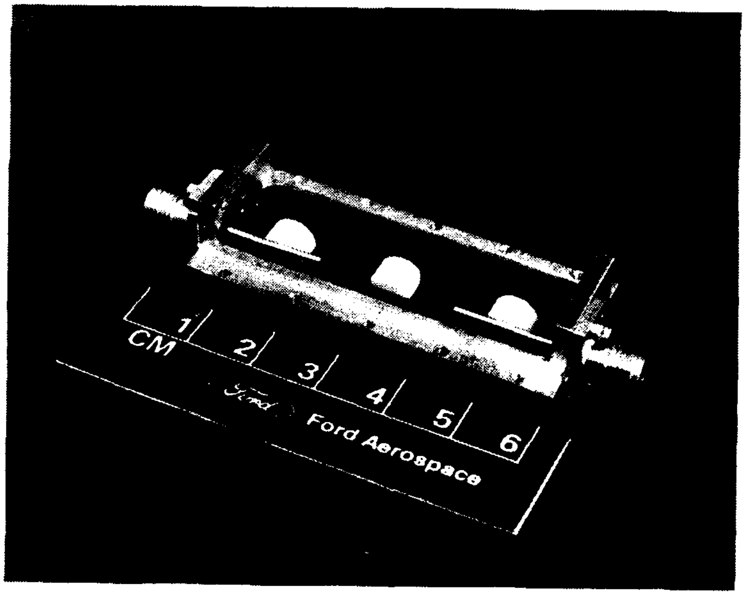


FIGURE 2.2-7 BB Half-Cut Dielectric Resonator Filter (3-pole).

300K

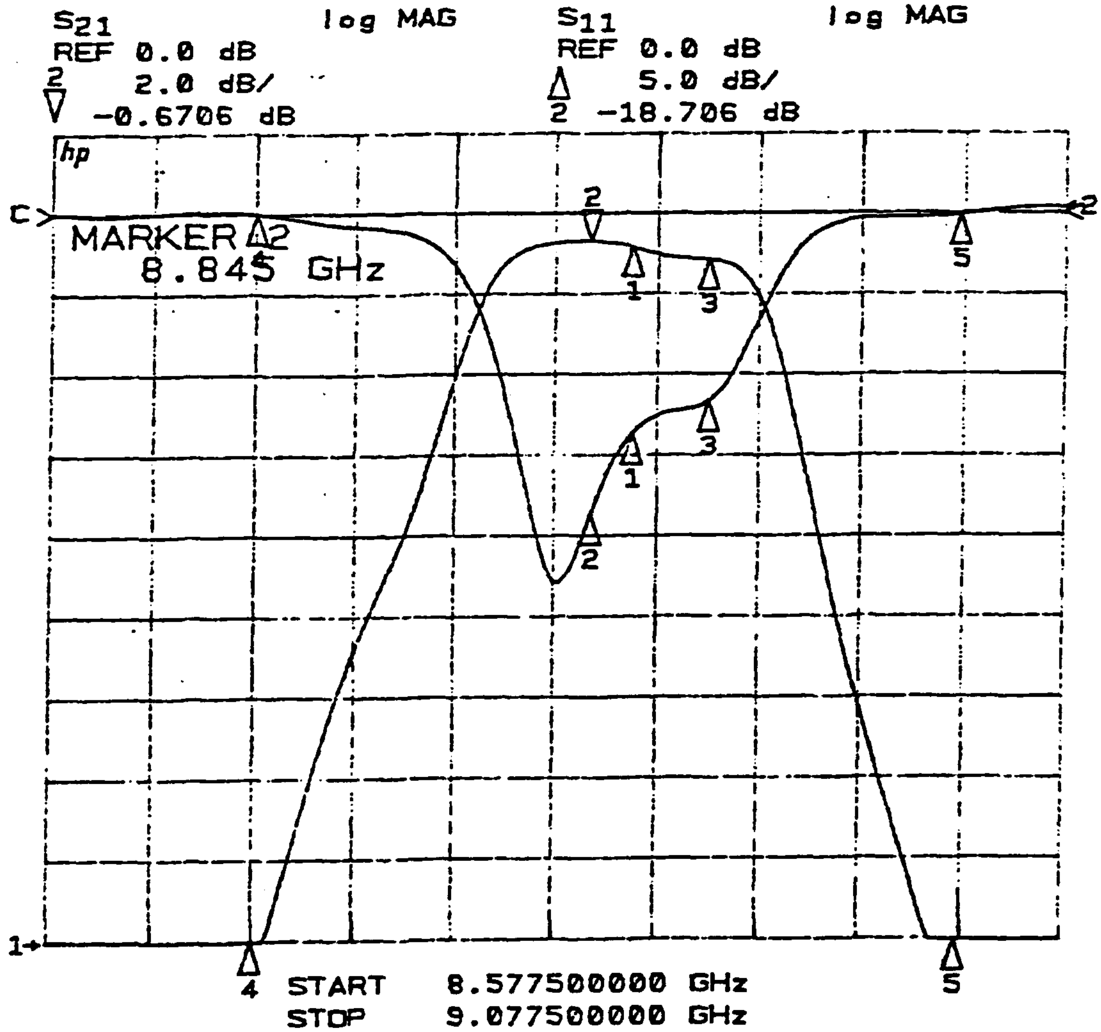


FIGURE 2.2-3 Performance of BB Half-Cut Dielectric Resonator Filter with Copper Plate @ 300K.

77K

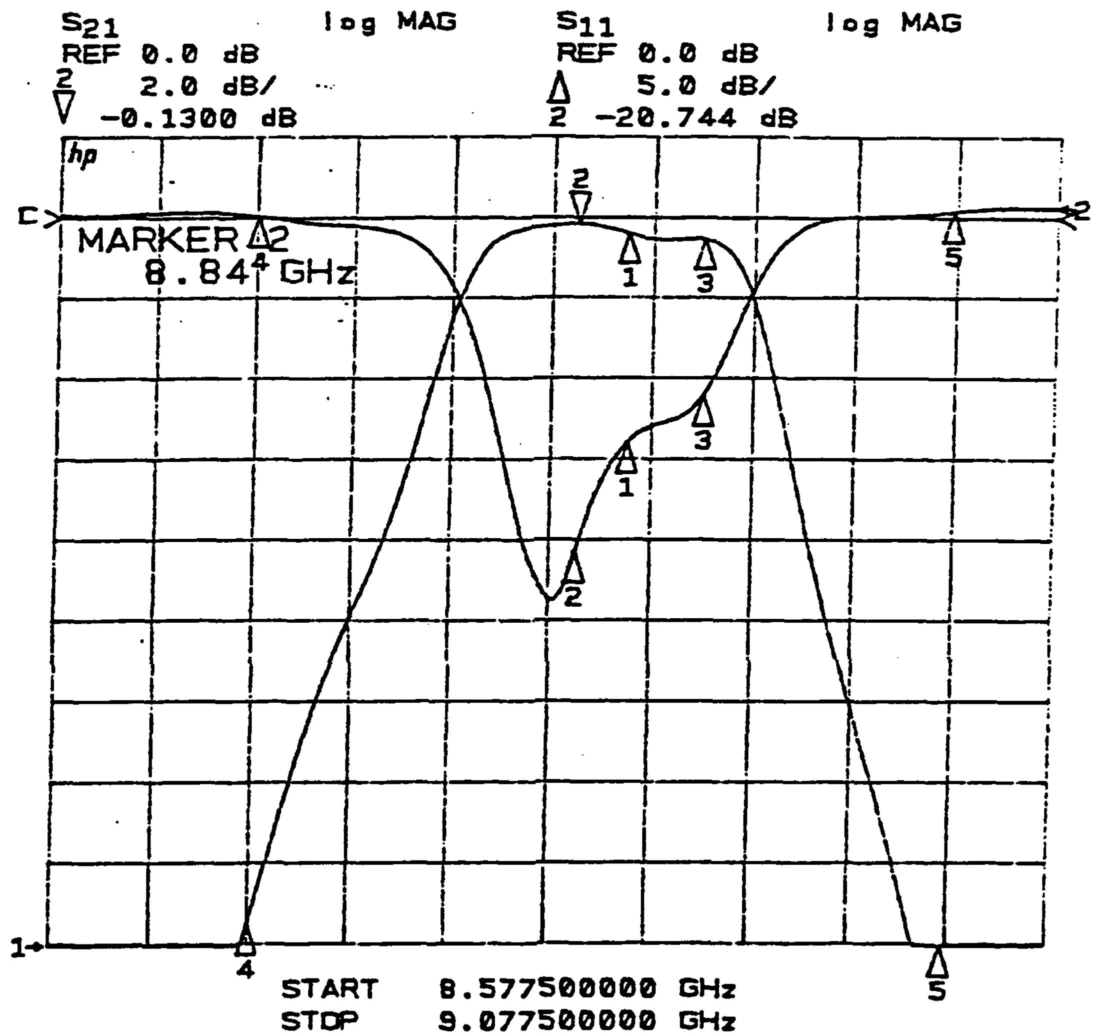


FIGURE 2.2-4 Performance of BB Half-Cut Dielectric Resonator Filter with Copper Plate @ 77 K.

300K

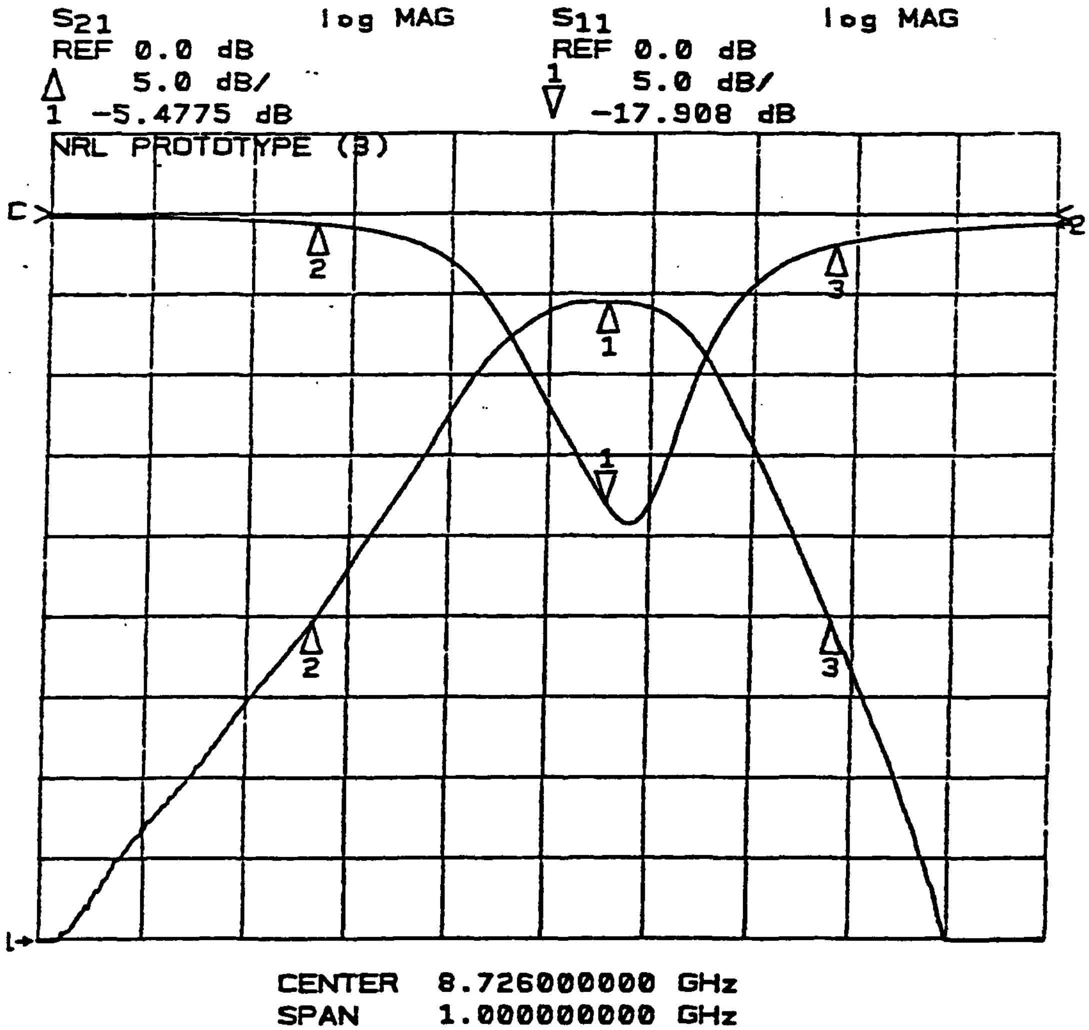


FIGURE 2.2-5 Performance of BB Half-Cut Dielectric Resonator Filter with Bulk YBCO Plate @ 300K.

77K

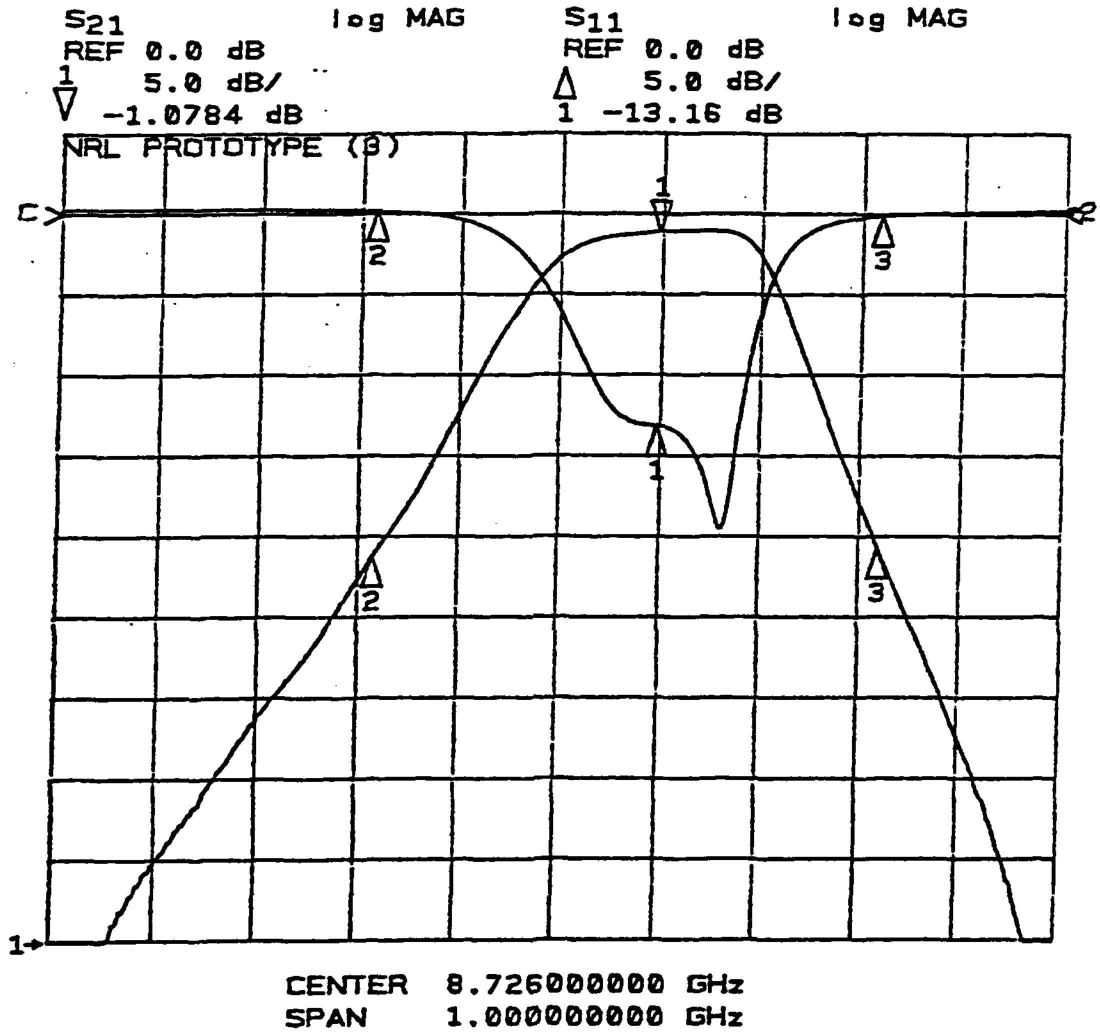


FIGURE 2.2-6 Performance of BB Half-Cut Dielectric Resonator Filter with Bulk YBCO Plate @ 77 K.

3.0 MEASURED PERFORMANCE OF DELIVERED DEVICES.

The techniques described in Section 3 of this report were used to design the flight model filters shown in Figures 1.0-3 through 1.0-6. The flight model filters were extensively tested by Space Systems/Loral. The resulting performance is the best of any superconducting filter reported to date. The key performance parameters measured are insertion loss, rejection, and return loss (S parameters). All measurements were performed using either an HP 8720B or HP 8510B network analyzer. Loss calibrations were performed at 77K to ensure accuracy of the measurements.

As expected, the performance of the filters is directly related to the quality of the HTS films used in the fabrication. The measured parameters of the HTS films used in the construction of the delivered devices is outlined in Section 4 of this report.

The delivered devices were serialized according to the following numbering scheme.

Full puck, 3-pole devices: FAC A-01 through FAC A-05
Half cut, 2-pole devices: FAC B-01 through FAC B-05

The performance plots shown in this report can be referenced to the units from which they were generated by the part number shown in the upper left hand corner of the plot. All non-room temperature data was taken at 77 Kelvin.

3.1 MEASURED PERFORMANCE OF THE 3-POLE FILTERS.

The following pages contain measured performance plots for the 3-pole, full puck filters. A description of the measured data is given below.

Figures 3.1-1 through 3.1-5 show the measured insertion loss, return loss, and narrow band, out of band rejection characteristics of the full puck devices FAC A-01 through FAC A-05 respectively. Figures 3.1-6 through 3.1-10 show the measured wide band rejection performance of the full puck filters. These plots illustrate the outstanding performance achieved from the full puck filters. The performance of these filters is summarized in Table 3.1-1 below. The limiting factor to the performance of these

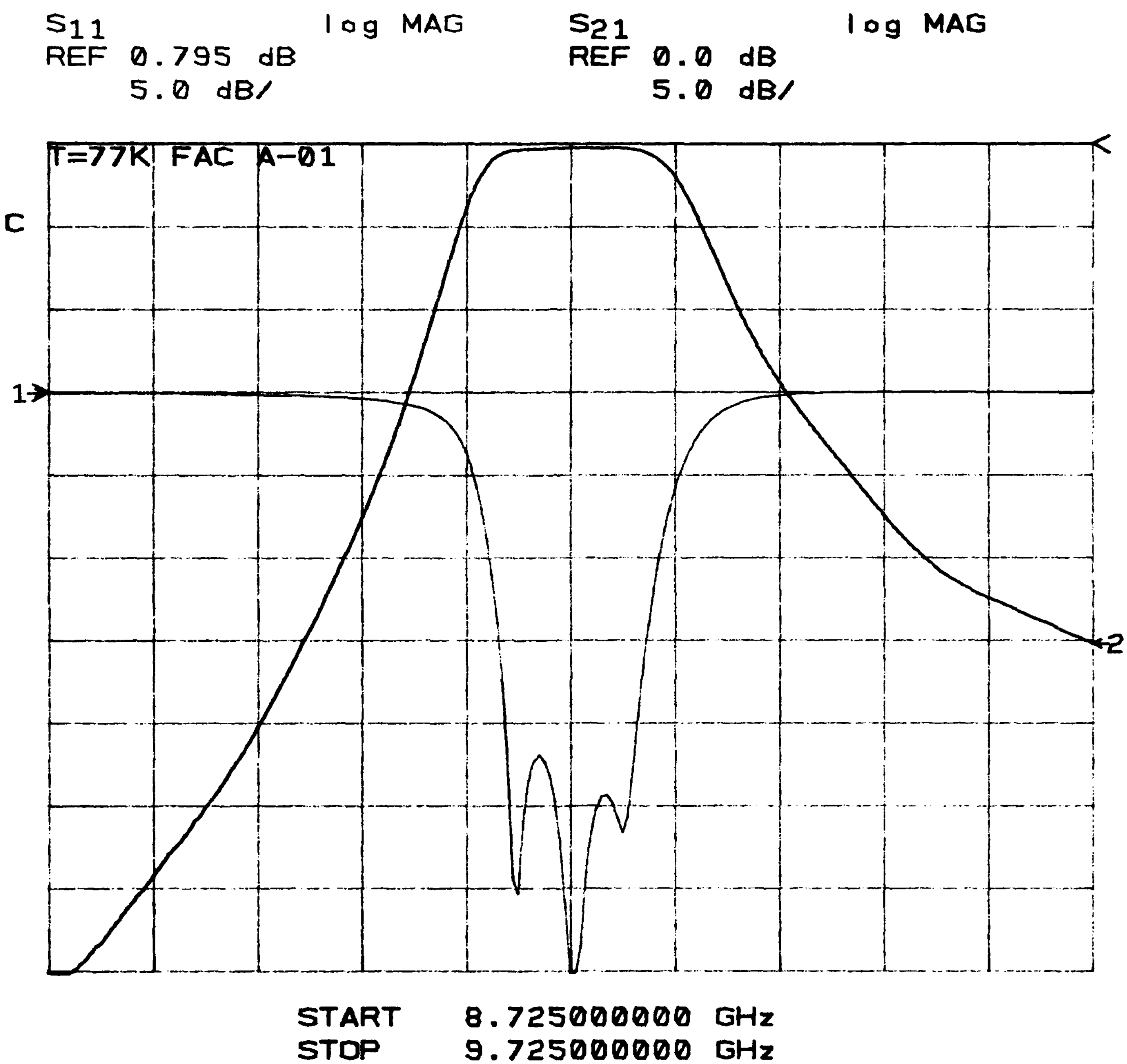


Figure 3.1-1 Measured Insertion Loss, Return Loss, and Narrowband Rejection Characteristics of FAC A-01.

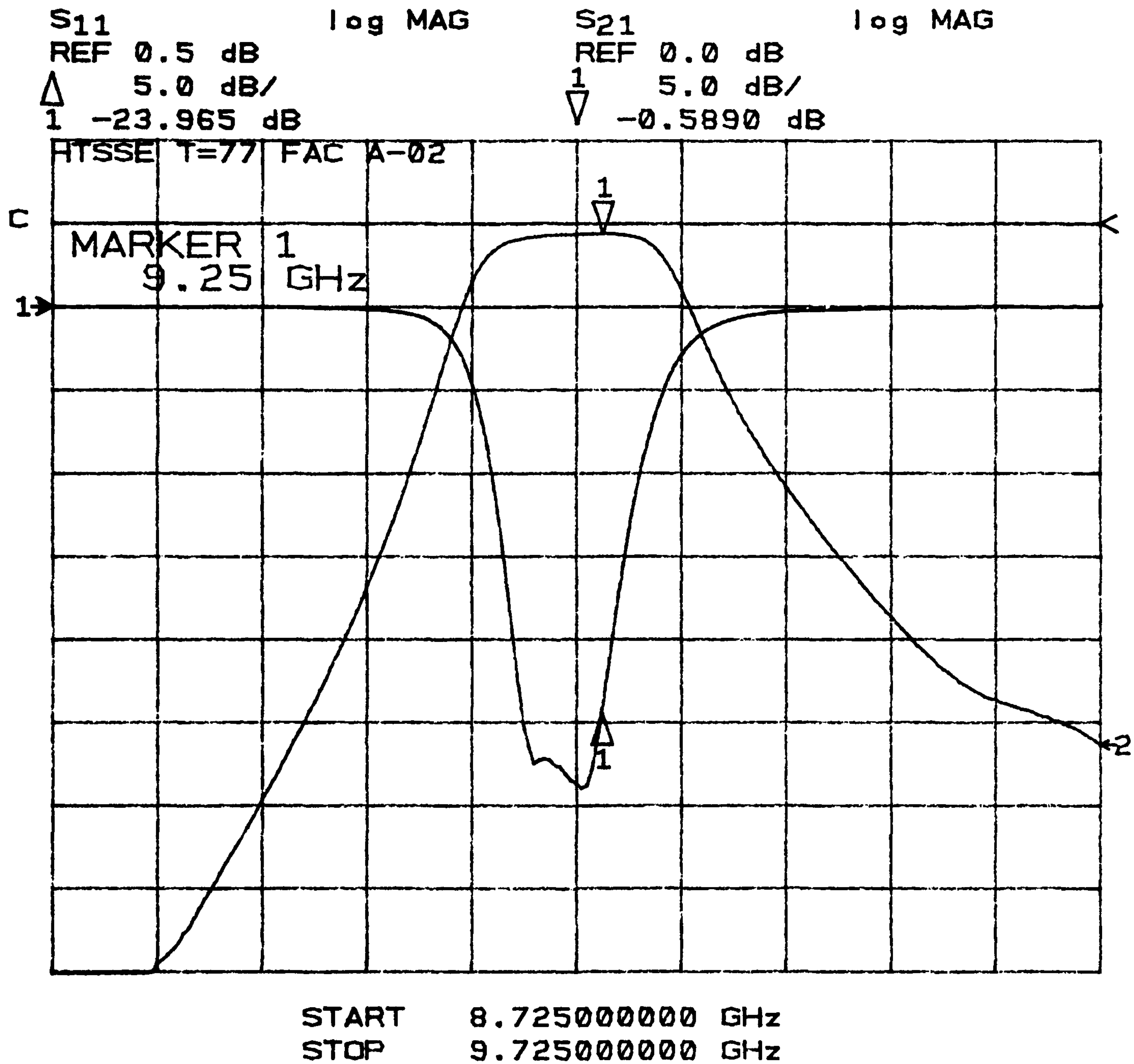


Figure 3.1-2 Measured Insertion Loss, Return Loss, and Narrowband Rejection Characteristics of FAC A-02.

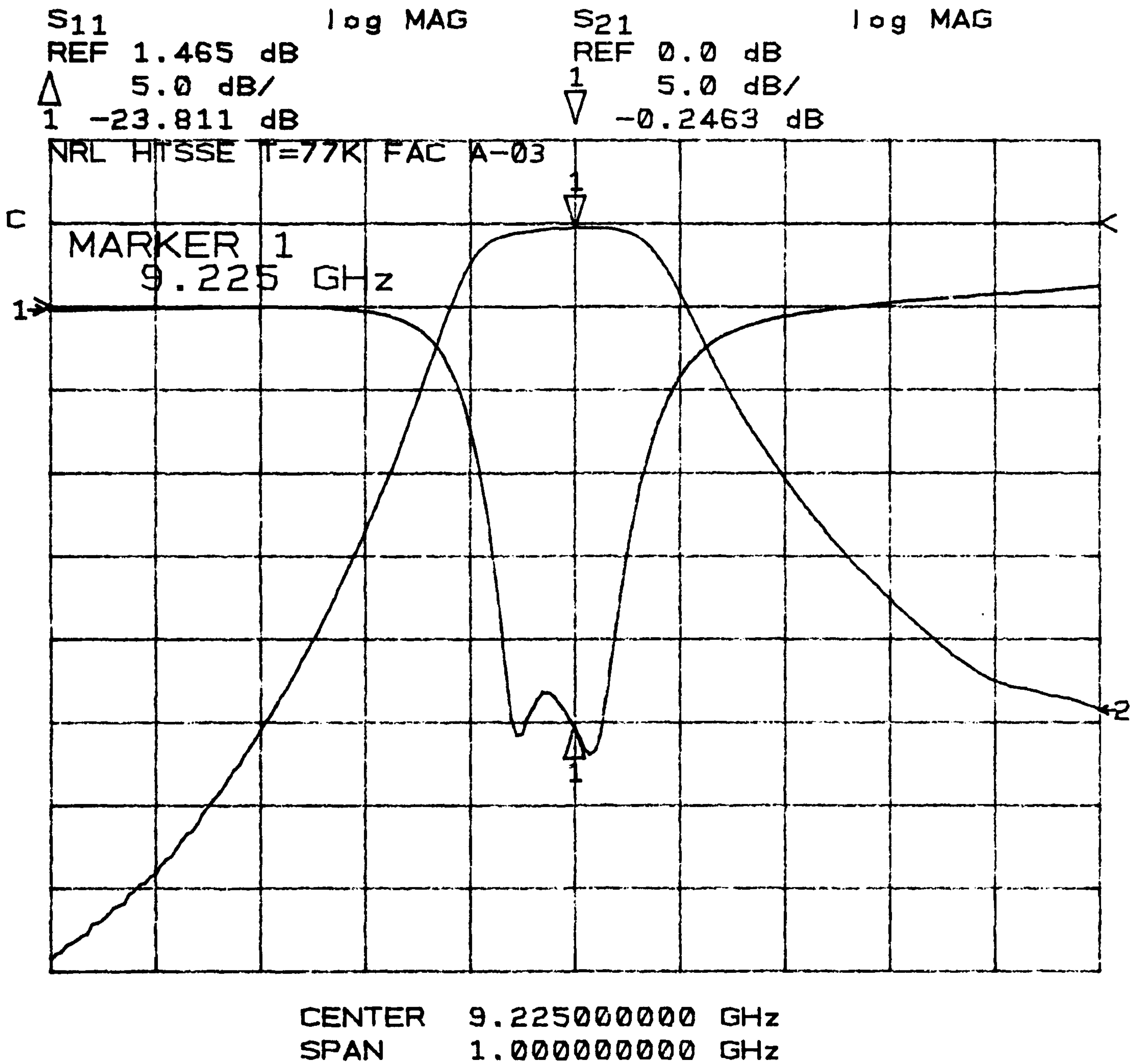


Figure 3.1-3 Measured Insertion Loss, Return Loss, and Narrowband Rejection Characteristics of FAC A-03.

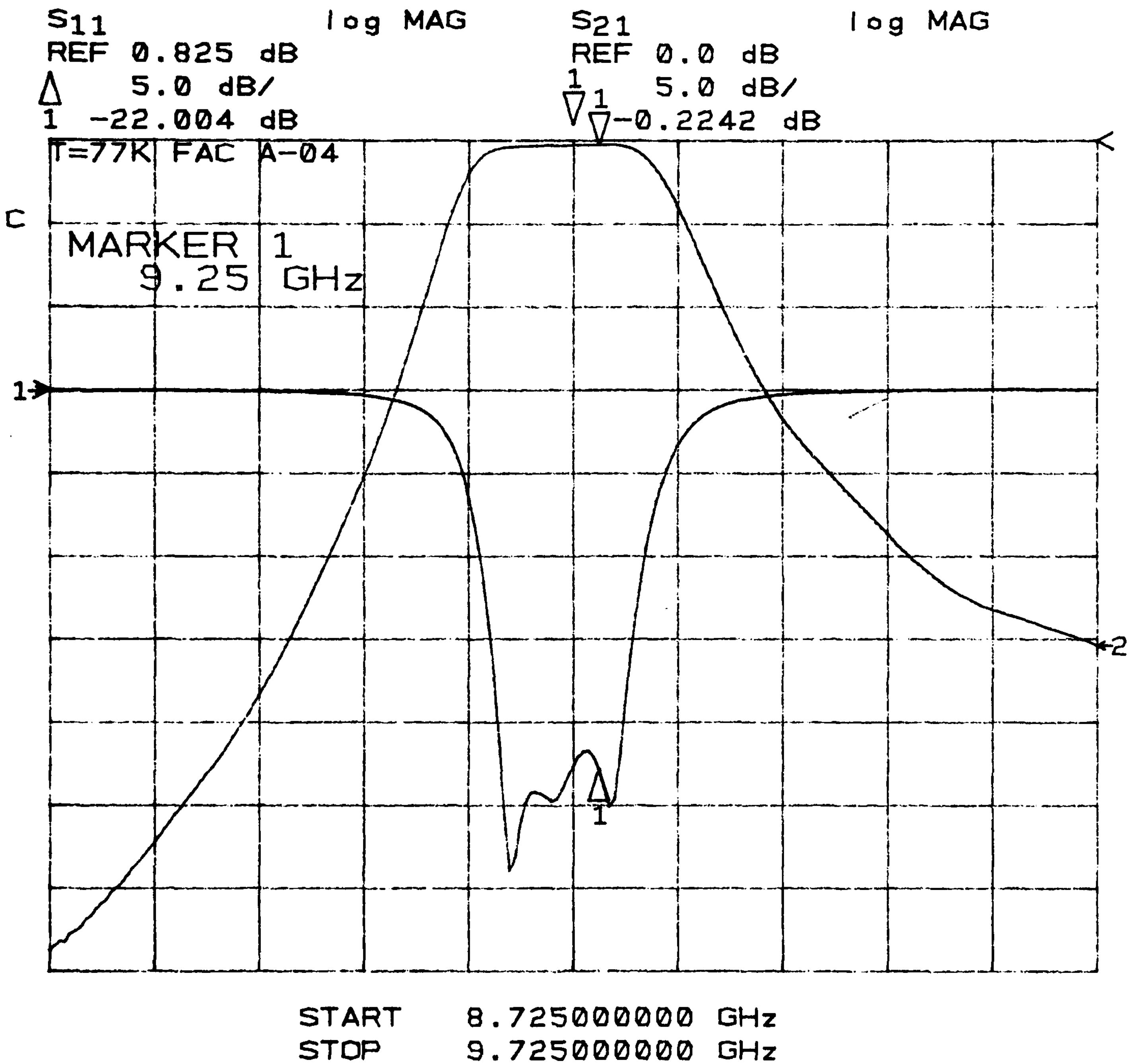


Figure 3.1-4 Measured Insertion Loss, Return Loss, and Narrowband Rejection Characteristics of FAC A-04.

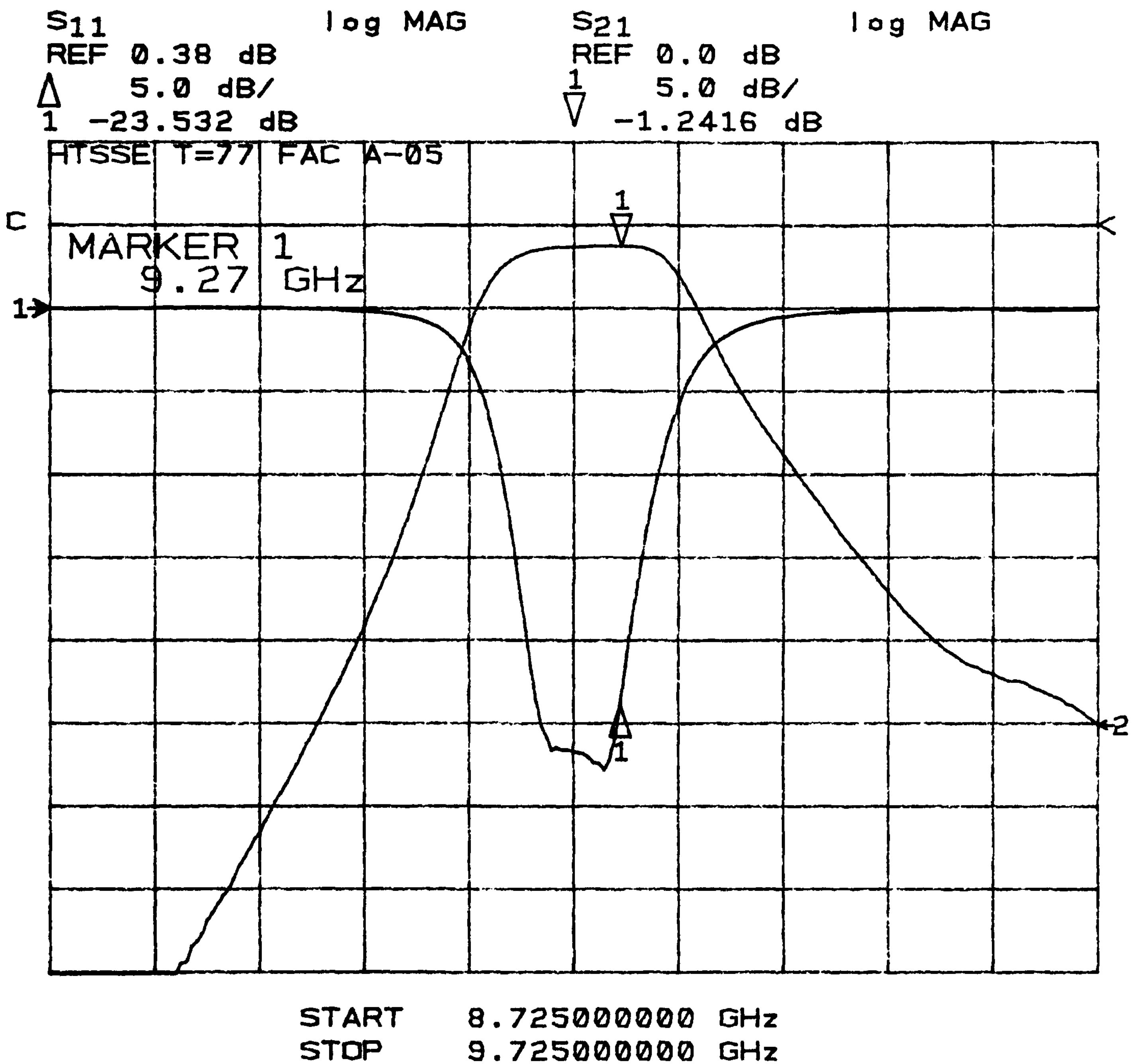


Figure 3.1-5 Measured Insertion Loss, Return Loss, and Narrowband Rejection Characteristics of FAC A-05.

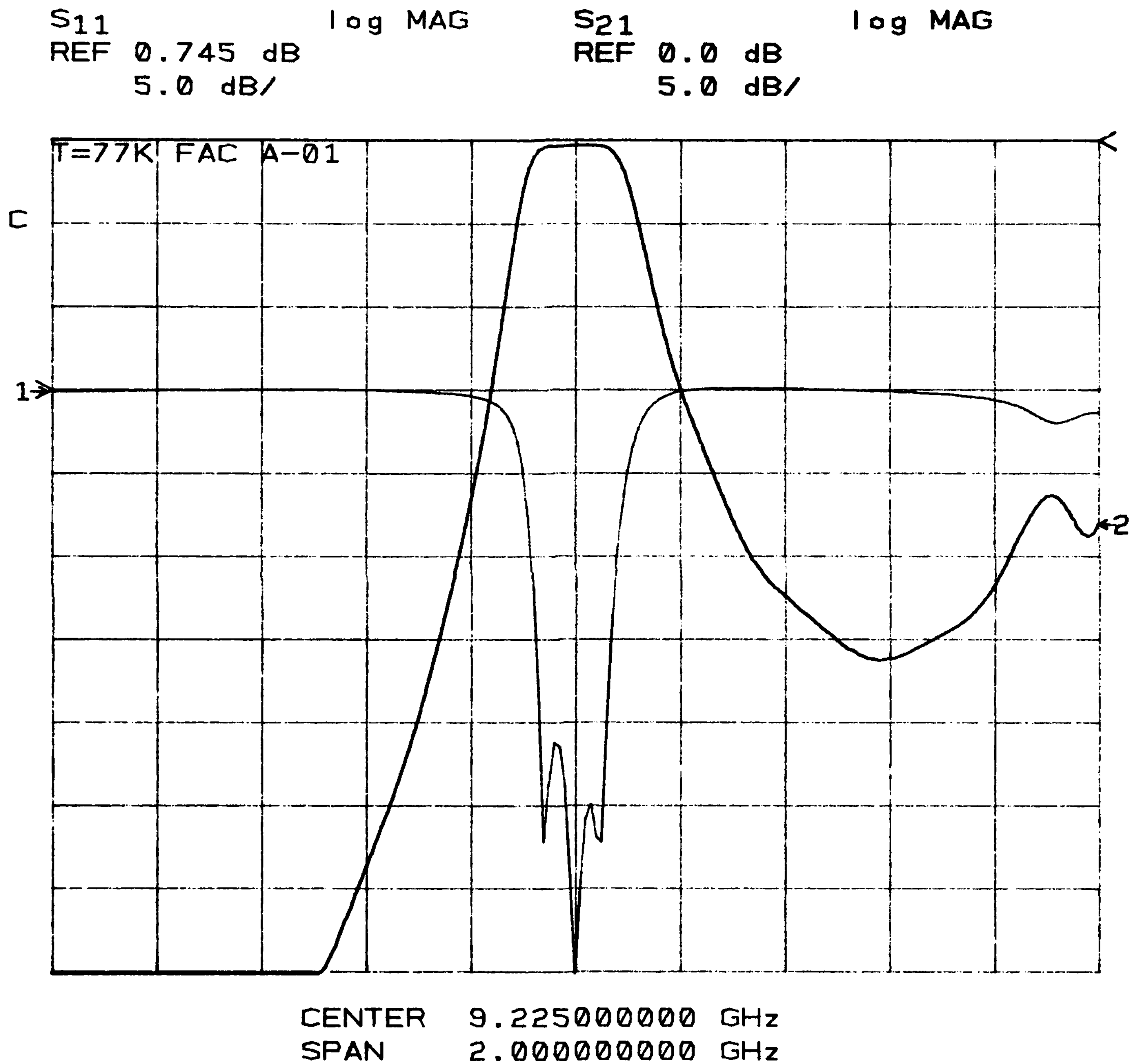


Figure 3.1-6 Measured Wideband Rejection Performance of FAC A-01.

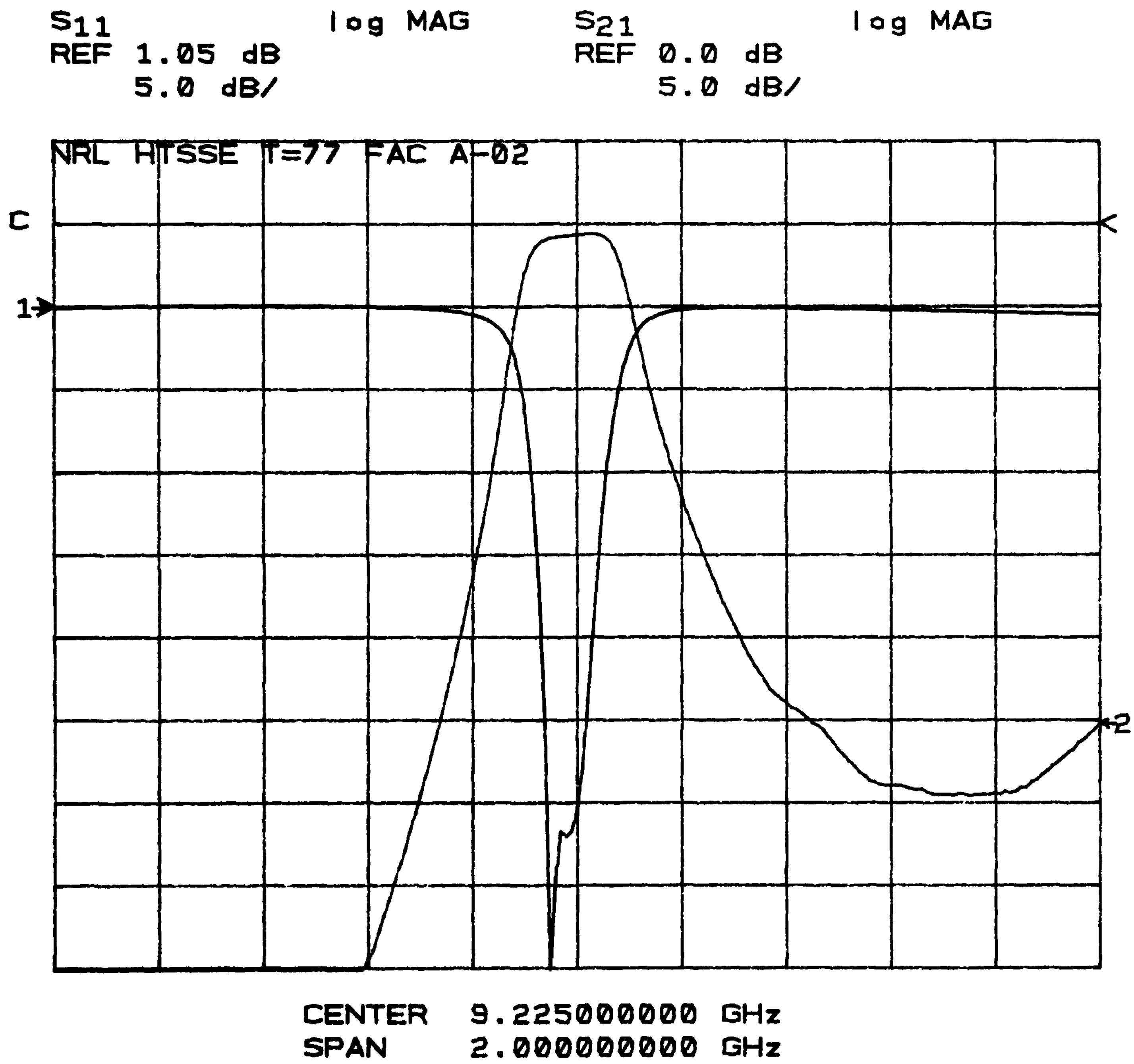


Figure 3.1-7 Measured Wideband Rejection Performance of FAC A-02.

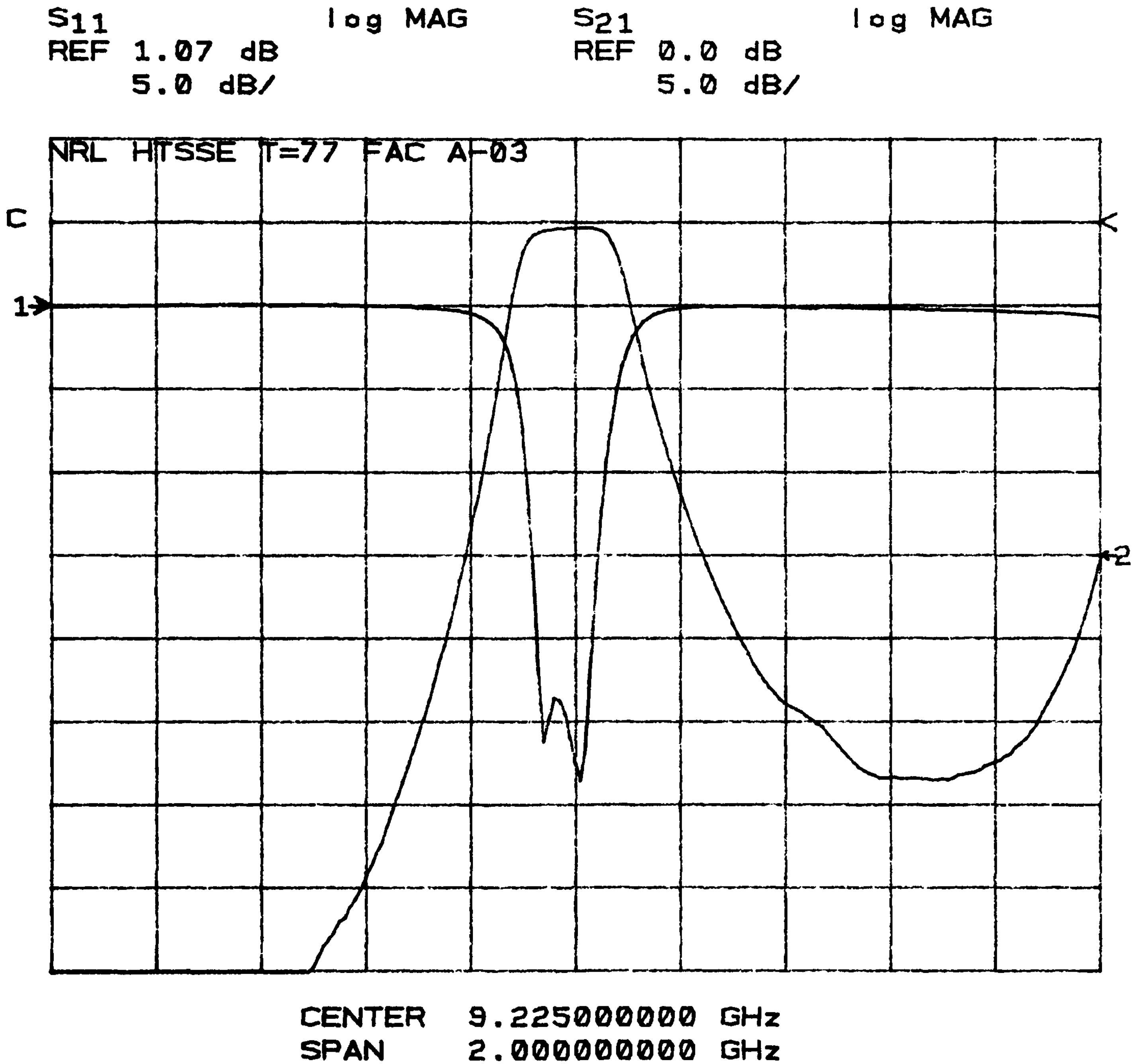


Figure 3.1-8 Measured Wideband Rejection Performance of FAC A-03.

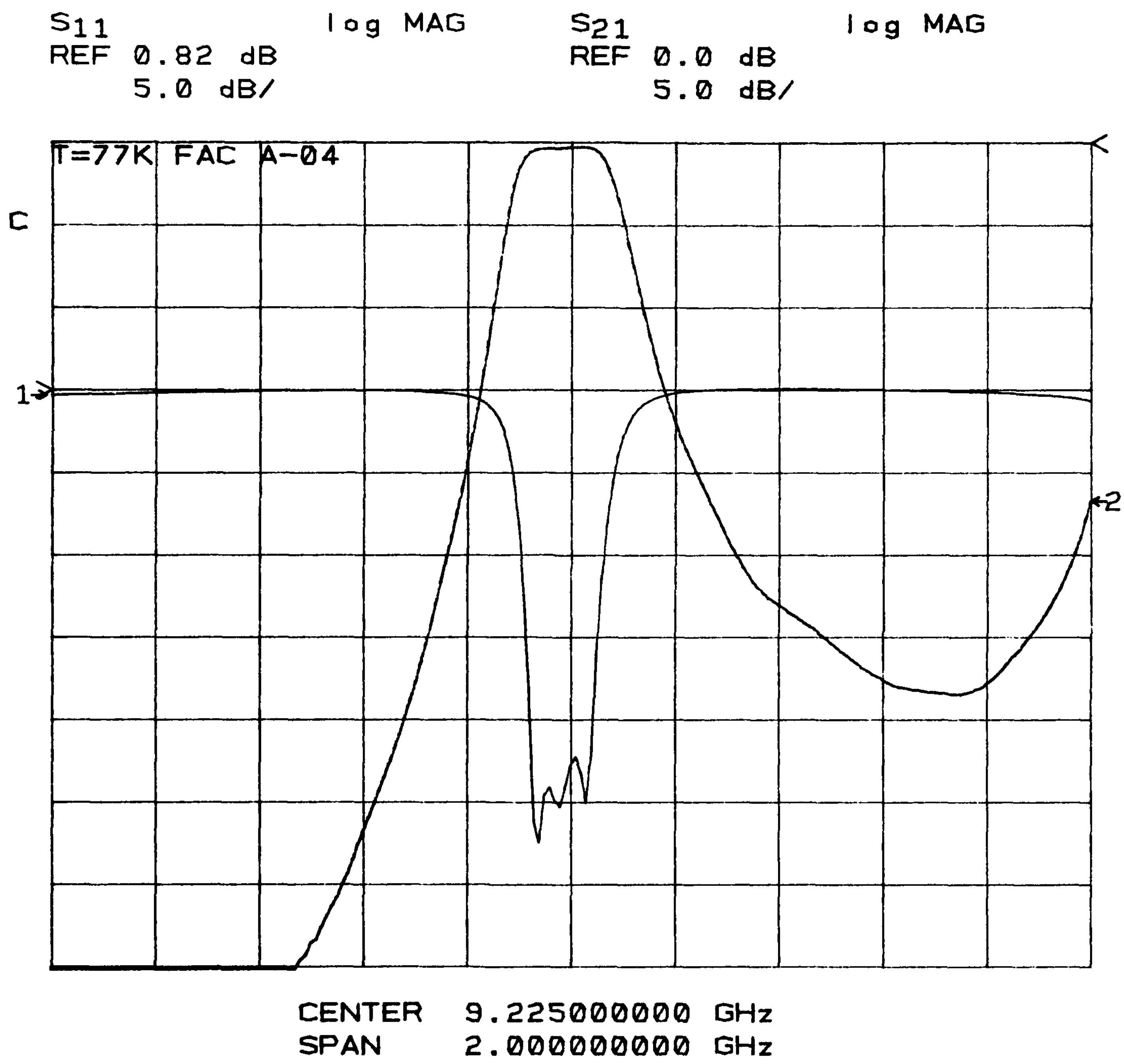


Figure 3.1-9 Measured Wideband Rejection Performance of FAC A-04.

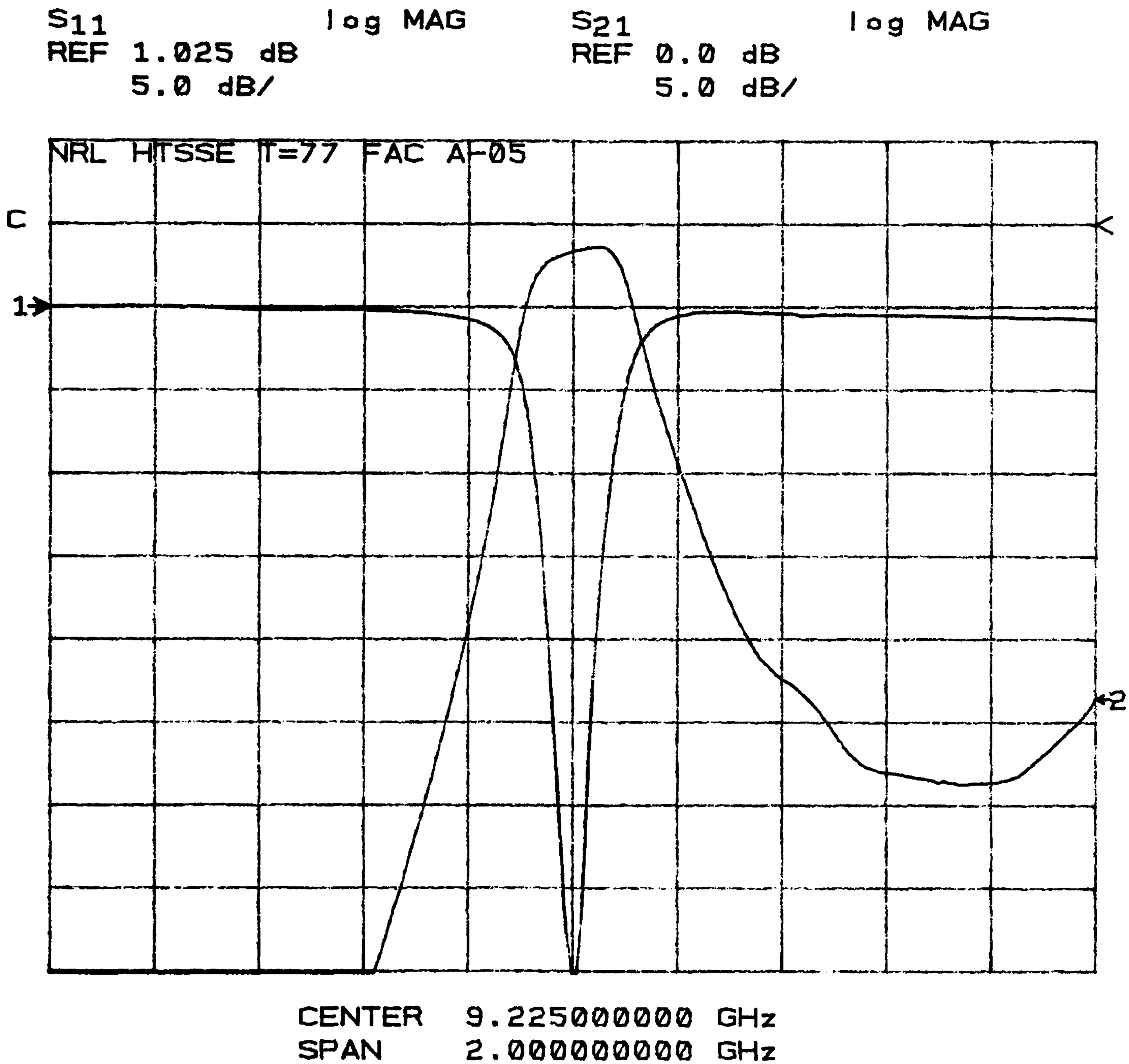


Figure 3.1-10 Measured Wideband Rejection Performance of FAC A-05.

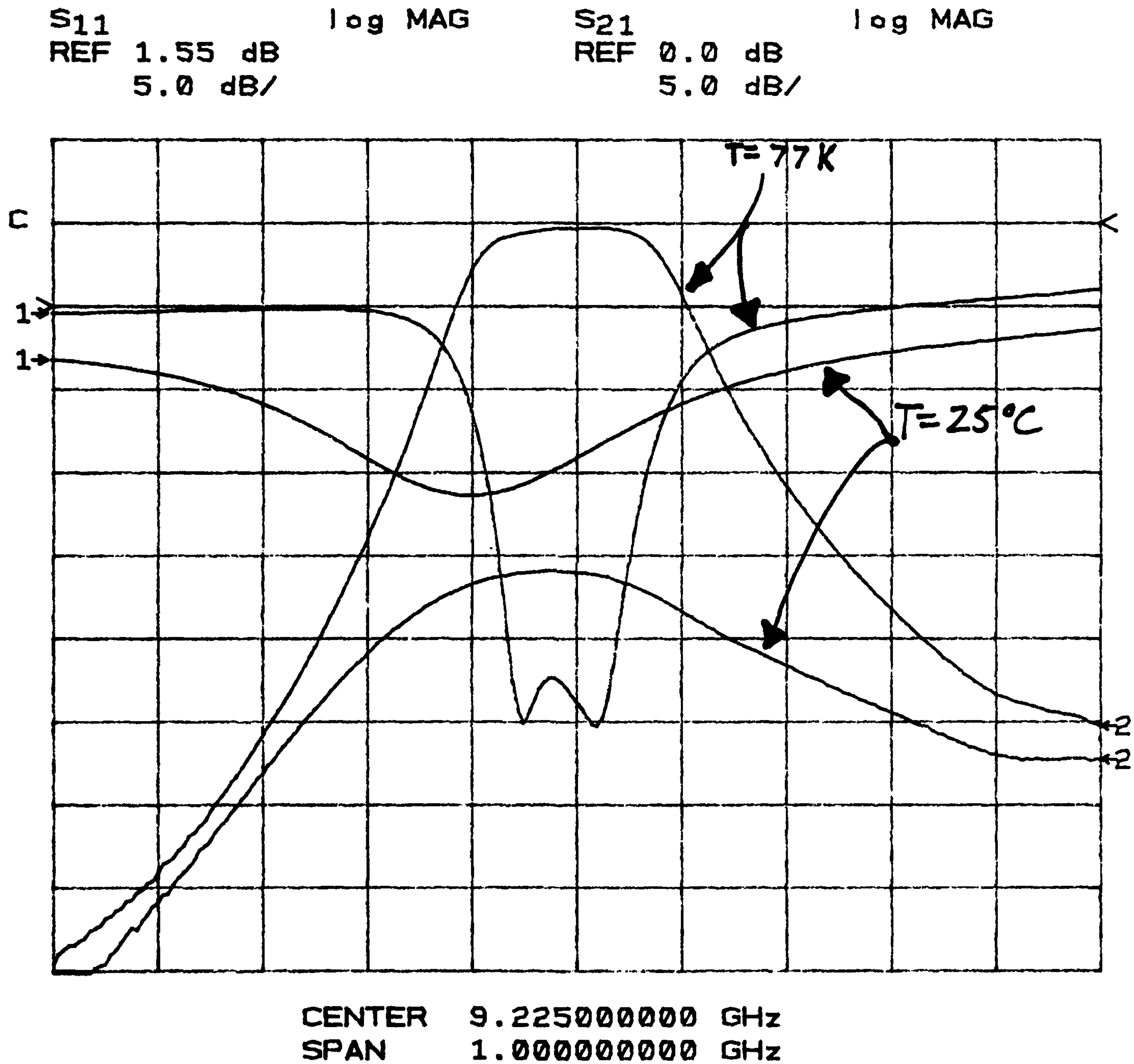


Figure 3.1-11 Comparison of the Insertion Loss and Return Loss For One of the 3-Pole Flight Model Filters at 25 C and 77 K.

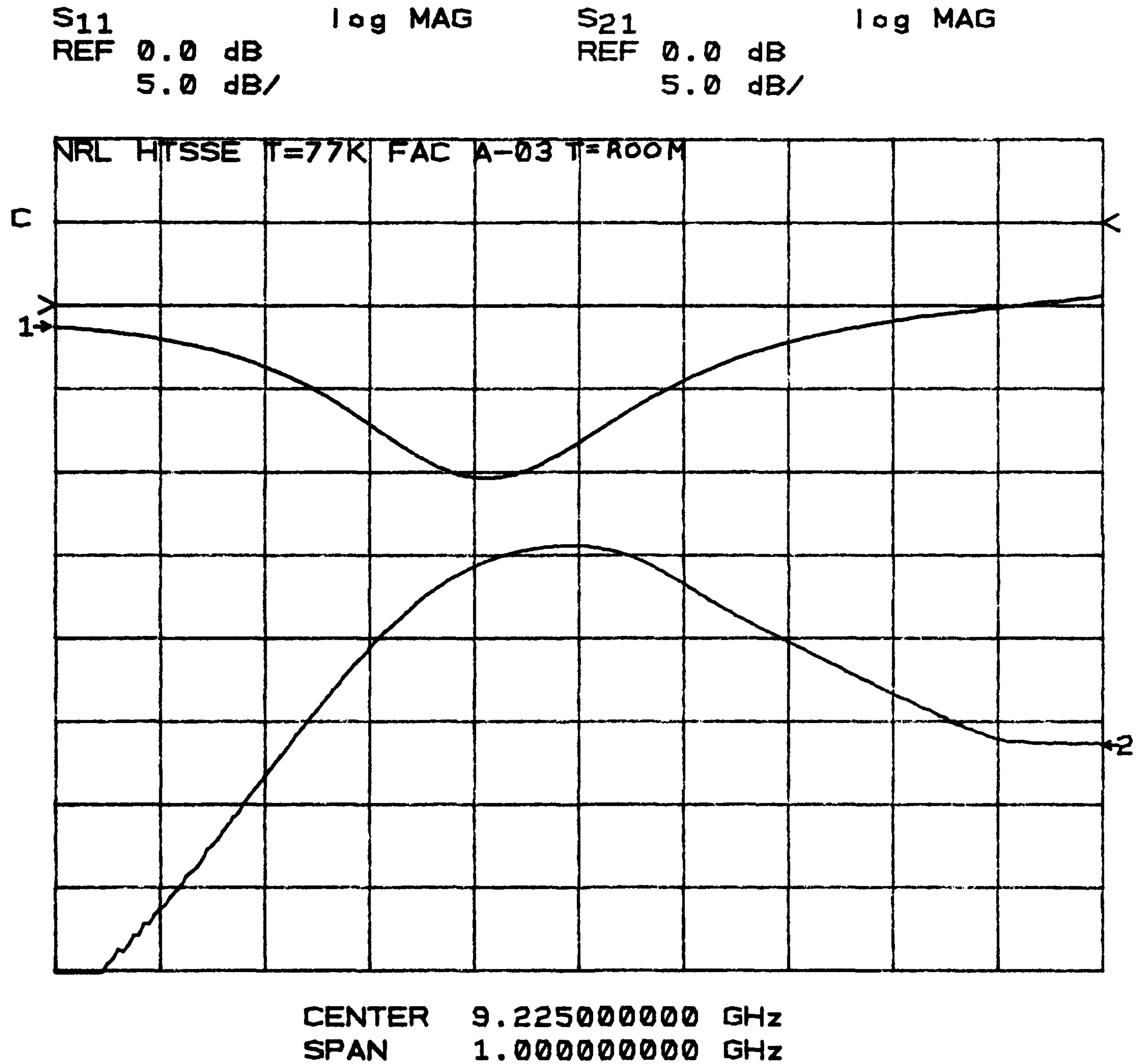


Figure 3.1-12 Measured Insertion Loss and Return Loss of FAC A-03 at Room Temperature.

filters is the non-superconducting aluminum side walls of the filter housing. This performance can be significantly improved by slightly increasing the spacing between the dielectric resonators and the housing walls.

FILTER PART NUMBER	CENTER FREQUENCY	20 dB USABLE BANDWIDTH	INSERTION LOSS	RETURN LOSS
FAC A-01	9.225 GHz	127 MHz	0.21 dB	22 dB
FAC A-02	9.225 GHz	124 MHz	0.58 dB	30 dB
FAC A-03	9.215 GHz	85 MHz	0.25 dB	23 dB
FAC A-04	9.217 GHz	118 MHz	0.22 dB	23 dB
FAC A-05	9.235 GHz	96 MHz	1.24 dB	27 dB

Table 3.1-1: Summary of the Performance Characteristics of the 3-Pole Filters

Figures 3.1-11 and 3.1-12 illustrate, for comparison, the room temperature performance of the full puck filters.

3.2 MEASURED PERFORMANCE OF THE 2-POLE, HALF CUT FILTERS.

The following pages contain measured performance plots for the 2-pole, half cut filters. While the half cut filters are smaller to the full puck filters, their performance was not nearly as good. The difference in the filter performance is partially a result of the half cut configuration, and partially because the quality of the HTS films available for the half cut filters was not as good as the films used for the full puck filters. A description of the measured performance data for the half cut filters is given below. Unless otherwise mentioned, all data was taken at a temperature of 77 K.

Figure 3.2-1 shows the measured insertion loss, return loss, and rejection performance of serial numbers FAC B-01 and FAC B-02. Figure 3.2-2 shows the measured performance of FAC B-03, FAC B-04, and FAC B-05. Figures 3.2-3 and 3.2-4 show the measured insertion loss and return loss of two of the half cut filters at room temperature for comparison.

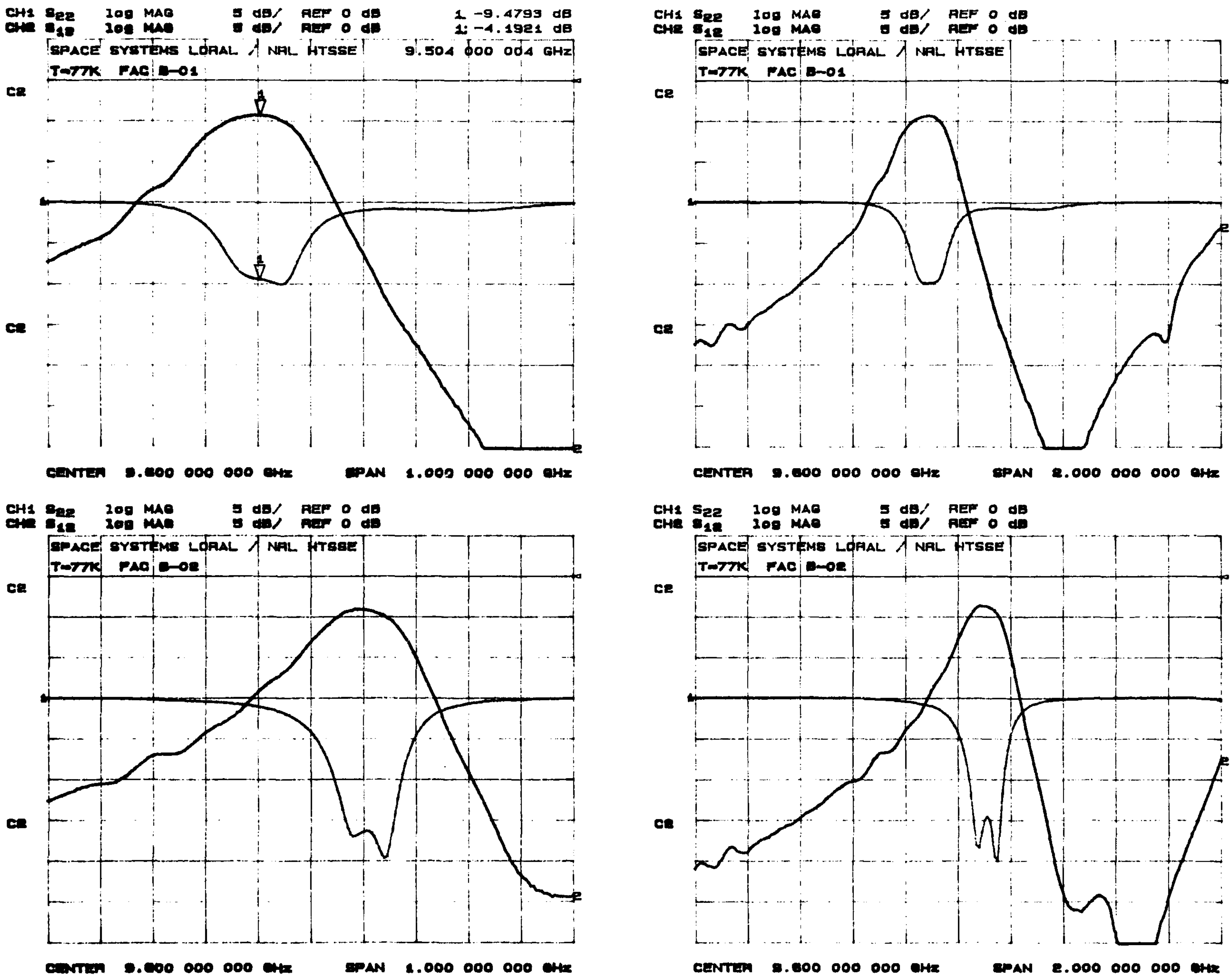


Figure 3.2-1 Measured Performance of Serial Numbers FAC B-01 (top) and FAC B-02 (bottom).

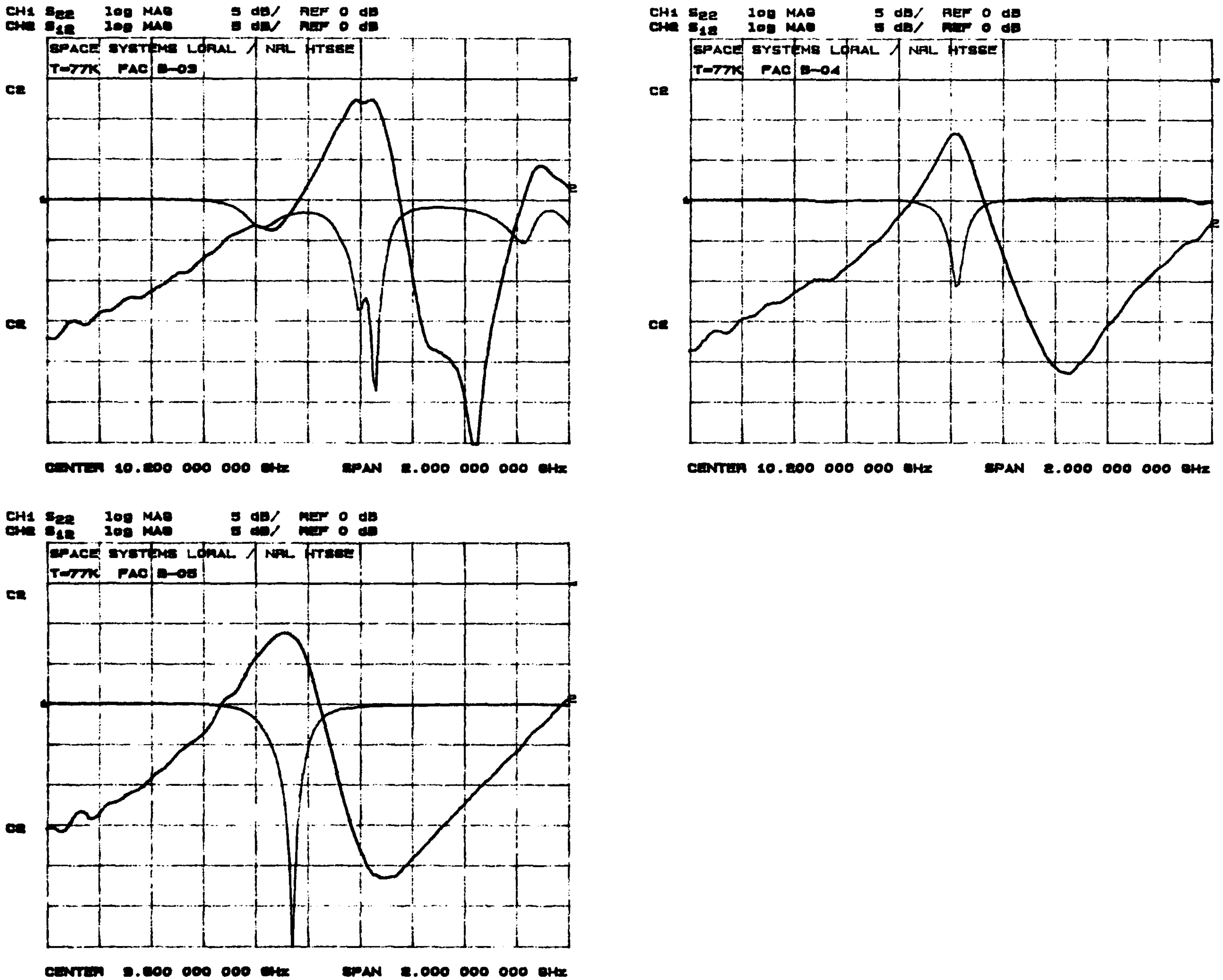


Figure 3.2-2 Measured Performance of Serial Numbers FAC B-03, FAC B-04, and FAC B-05.

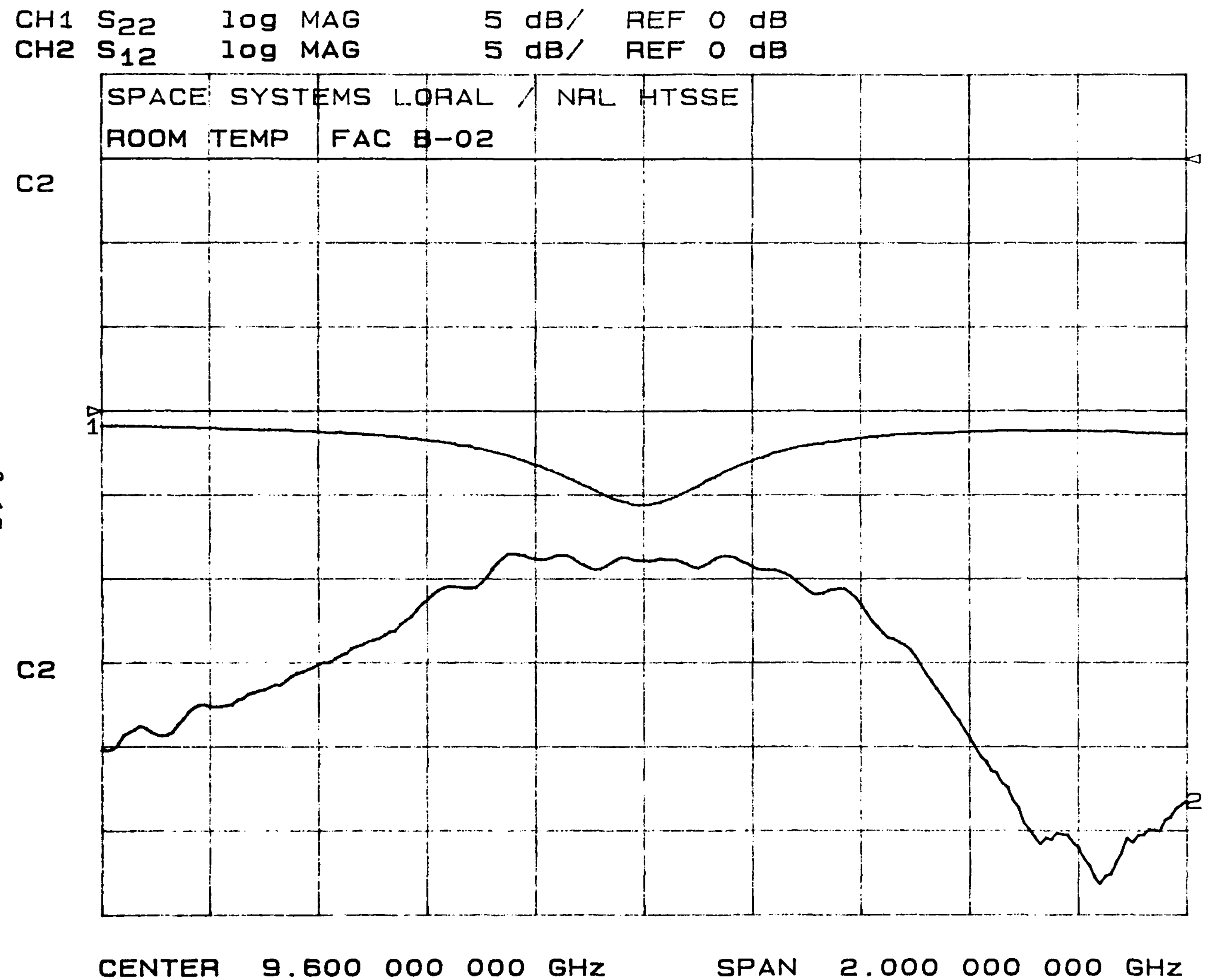


Figure 3.2-3 Measured Insertion Loss and Return Loss Performance of One of the Half Cut Filters at Room Temperature.

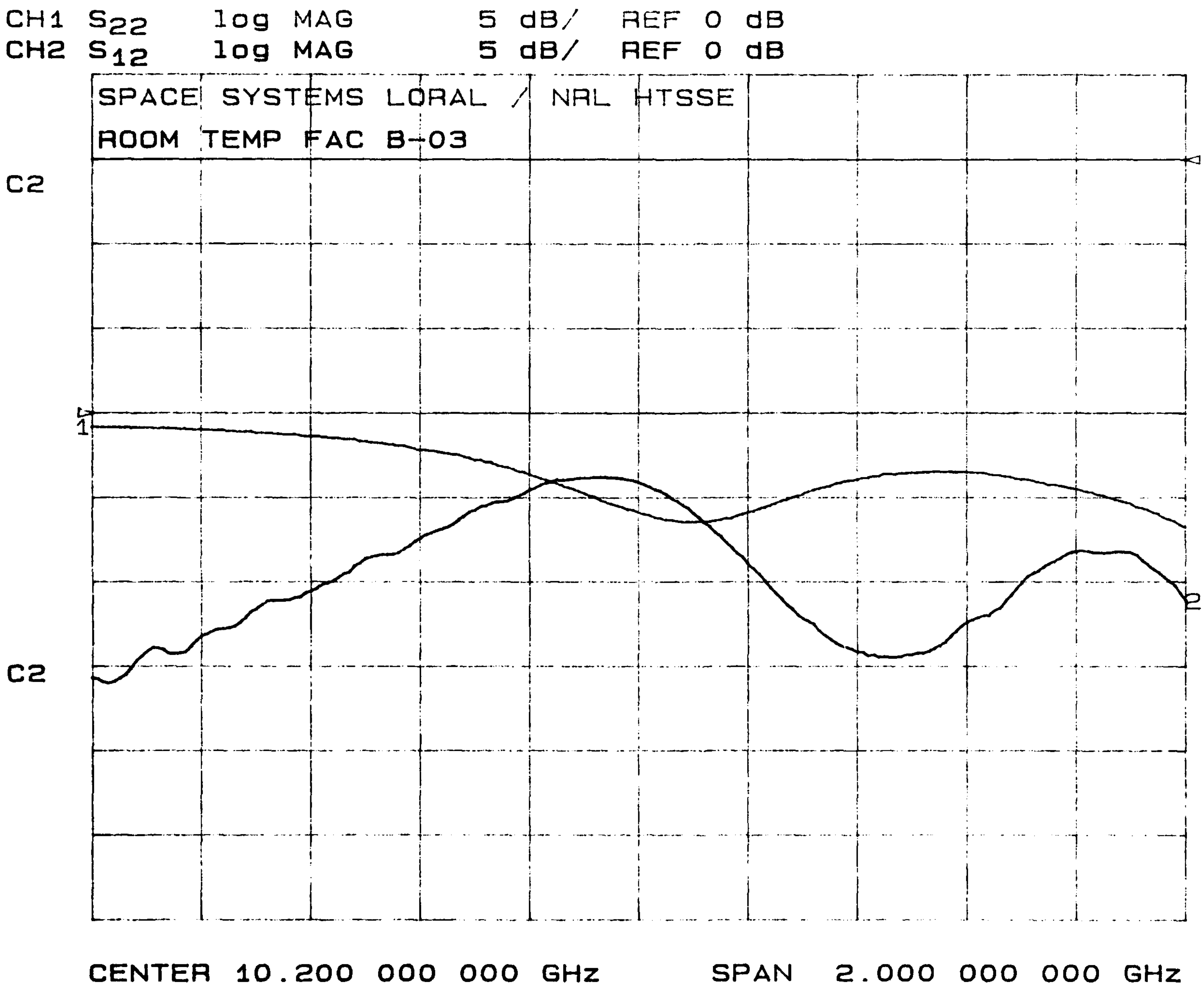


Figure 3.2-4 Measured Insertion Loss and Return Loss Performance of One of the Half Cut Filters at Room Temperature.

4.0 PROPERTIES OF HTS FILMS USED IN THE DELIVERED DEVICES.

In the fabrication of the 10 filters delivered by Space Systems/Loral to NRL for HTSSE, we used two different superconductor materials, two different substrate materials, and a combination of films from four different sources. The sources of films and a brief description of some of their properties is outlined below. The distribution of the films in the delivered filters is illustrated in Figure 4.0-1.

<u>NASA Lewis Research Center</u>

- YBCO on Lanthanum Aluminate
- Deposited by Laser In Situ Ablation
- T_c for films used is 88 - 90 K
- Rs varies between 1/5 and 5 times that of copper at 77 K for films used

<u>Ford Scientific Research Laboratories</u>

- YBCO on Lanthanum Aluminate
- Deposited by Sputtering with Post Deposition Anneal
- T_c for films used is 88 - 90 K
- Rs varies between 1 and 5 times that of copper at 77 K for films used

<u>Superconductor Technologies Incorporated</u>

- Thallium Films on Lanthanum Aluminate
- Deposited by Laser Ablation with Post Deposition Anneal
- T_c for films used is 101 - 103 K
- Rs varies between 1/10 and 1/30 times that of copper at 77 K for films used

<u>CVC Products</u>

- YBCO on Magnesium Oxide
- Deposited by Sputtering with Post Deposition Anneal
- T_c for films used is unknown
- Rs is approximately 4 times that of copper at 77 K for the film used

The two most important properties of the films used for this application are the critical temperature (T_c) and the microwave surface resistance (R_s). The films used by SS/L for the HTSSE program were screened using the dielectric resonator probe surface resistance measurement technique. Clearly, the performance of the the filters delivered is better for the filters fabricated using the films with the lowest R_S and the highest T_C. An overview of the dielectric probe measurement technique is given in Appendices A, B and C of this report. The Q measurements from the dielectric probe measurements for each of the films used are given in Appendix G of this report.

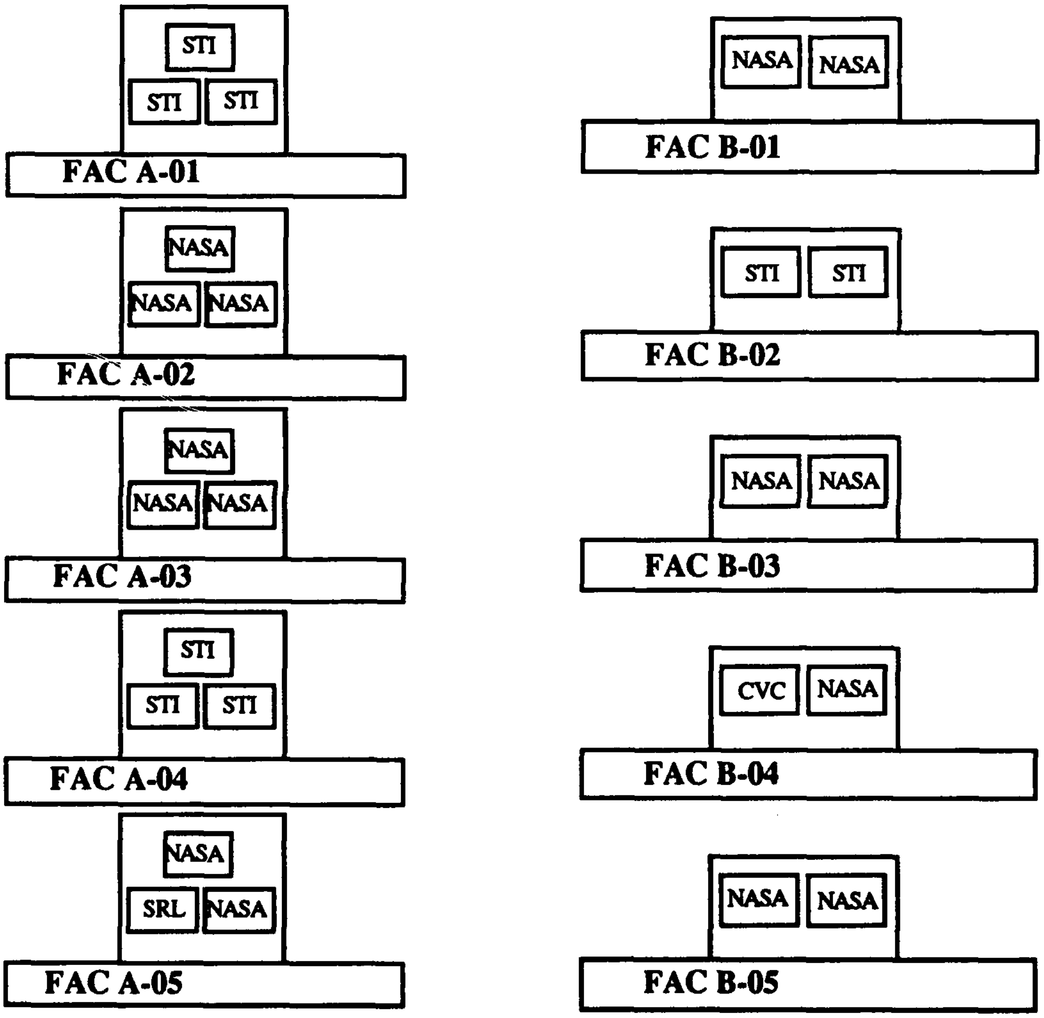


Figure 4.0-1: Illustration Showing the Sources of Films Used For Each Delivered Device

5.0 SUMMARY.

In this program, novel filter configurations utilizing dielectric resonators in combination with High Temperature Superconductors (HTS) were successfully developed and flight qualified for the High Temperature Superconductivity Space Experiment (HTSSE).
All program goals were met and the developed filters exhibit the best electrical performance (extremely low insertion loss) reported to this date. Several papers were published and presented and a patent application has been filed.

The developed dielectric resonator probe technique for measurements of properties of HTS was instrumental to the success of the program, allowing for rapid selection of HTS films for flight filters.

Filters and resonator configurations developed on this program have the potential for extremely high Q factors (in the order of tens of millions) when very low loss , high dielectric constant materials such as sapphire (or similar compounds) are used. Higher power handling and precise tuning of the filters is also possible.

In summary, this has been an extremely successful program which demonstrated the potential of HTS for high performance space applications.

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[1] S.J. Fiedziuszko ," Dual Mode Dielectric Resonator Loaded Cavity Filters" , IEEE Transactions on Microwave Theory and Techniques, Vol.MTT-30, pp.1311-1316, September 1982.

[2] R.J.Cameron, Wai-Cheung Tang, C.M. Kudsia, " Advances in Dielectric Loaded Filters and Multiplexers for Communication Satellites", Proc. of 13th AIAA International Communication Satellite Systems Conference, Los Angeles, pp.823-828, March 1990.

[3] K.A.Zaki, et al. " Canonical and Longitudinal Dual Mode Dielectric Resonator Filters Without Iris" IEEE Transactions on Microwave Theory and Techniques, vol. MTT-35, pp. 1130-1135, December 1987.

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[7] Y.Kobayashi, et al. " Frequency and Low-Temperature Characteristics of High-Q Dielectric Resonators" 1989 IEEE MTT-S International Microwave Symposium Digest, pp.1239-1242, June 1989.

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APPENDICES

APPENDIX A

DIELECTRIC RESONATOR USED AS A PROBE FOR HIGH Tc SUPERCONDUCTOR MEASUREMENTS

DIELECTRIC RESONATOR USED AS A PROBE FOR HIGH Tc SUPERCONDUCTOR MEASUREMENTS

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Ford Aerospace Corporation
Space Systems Division
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ABSTRACT

A novel probe for high Tc superconductor measurements based on the post dielectric resonator is described. Advantages of the device and the method of measurements include high sensitivity, simplicity, ability to measure small superconductor samples and nondestructive measurements of selected areas of larger samples including thin film superconductors. The technique and selected results are presented.

INTRODUCTION

The newly developed high temperature superconductors offer exciting possibilities for microwave and millimeter wave components and subsystems. Reduced surface resistance of the superconductor at microwave frequencies as compared to traditional metals is expected to significantly improve performance of these components. For this reason, proper microwave characterization of high Tc superconductors is crucial. Different characterization techniques for microwave surface resistance are described in [1].

The techniques include use of a cylindrical cavity operating in the TE011 mode (shown in Figure 1), disk resonator, stripline and coaxial resonators, and finally, a cavity perturbation technique. However, all these techniques have certain drawbacks. A method utilizing the TE011 cavity requires relatively large samples of superconductor material (greater than 5 cm^2 for frequencies below 20 GHz) if measurements need to be performed at lower microwave frequencies. Also, the cavity is only partially superconducting and losses in the metal side wall dominate Q value, reducing sensitivity and accuracy of measurements.

The TE011 mode dielectric filled high Tc superconductor cavity described in [2] is difficult to make from bulk material, air gaps are a problem, and at the present time it is impossible to realize such a cavity with thin film superconductor. The disk resonator method is very promising, however, large samples of superconductor are also required. Stripline or coaxial resonator methods can be used to measure over a wide range of frequencies, however, test resonators must be manufactured from supercondutive samples (thin film or bulk material). The perturbation method requires very small samples of the material, and in the case of high Tc superconductors, the best results were obtained using superconductive niobium (low Tc) for the test cavity.

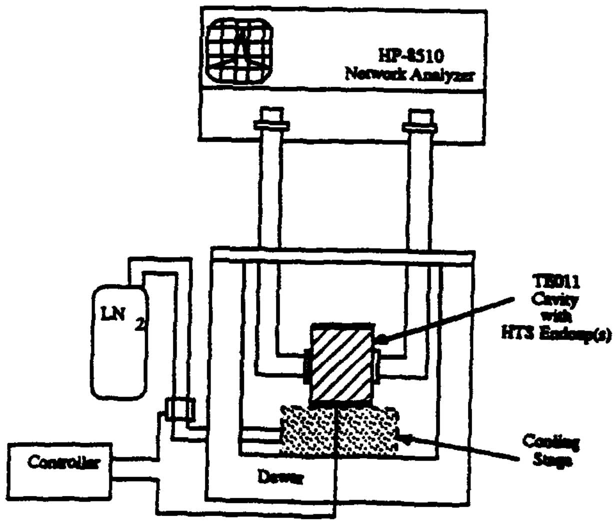

Figure 1 Cavity Q Measurement Technique

In this short paper, a novel method based on a post dielectric resonator is proposed for high Tc superconductor resistivity measurements. A basic principle of the method is well known and widely used for dielectric constant and loss tangent measurements of materials for dielectric resonators (Hakki-Coleman method [3] with numerous modifications [4-6]). In all these methods, significant effort was devoted to calibrate out surface resistance of conductive walls. In our case, these methods will be evaluated and modified to obtain surface resistance and calibrate out loss tangent of the dielectric material. Advantages of the proposed method and fixture for measurements (probe) include the ability to measure small samples of superconductor at lower microwave frequencies, the possibility of probing different areas on a sample such as a large superconductive thin film, simplicity, and accuracy. Since end walls of the post resonator are the main contributors to Q factor, and side walls are absent, the method is much more sensitive then the TE011 mode cavity method. An additional advantage is related to the fact that the method is nondestructive and many different samples can be measured using the proposed fixture (probe) and later used to manufacture an actual device such as a resonator.

DIELECTRIC PROBE STRUCTURE AND MEASURING TECHNIQUE

The basic configuration of the proposed dielectric resonator probe is shown in Figure 2. A circular dielectric resonator is attached on one side to a copper plate, which also serves as a support for input and output coupling probes (the resonator is weakly coupled). The bottom plate serves as a calibration surface and also can be used as a support for the high Tc superconductor sample- typically in the form of a disk or plate. The TE011 mode is used for measurements in a fashion similar to that described by e.g. Kobayashi [6]. The field configuration of this particular mode is shown in Figure 3. The TE011 mode is easily identified, relatively insensitive to small gaps between dielectric and conductive plates, and due to its field configuration, has no axial currents across any possible joints in conductive plates (similar to the TE011 mode in circular metal cavity). Typical resonant modes of the structure are shown in Figure 4.

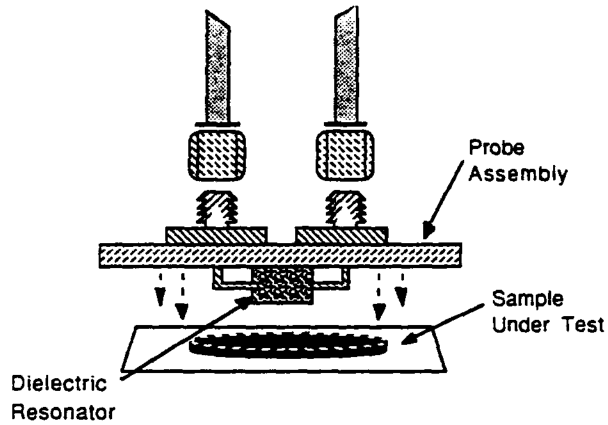

Figure 2 Dielectric Resonator Probe Assembly

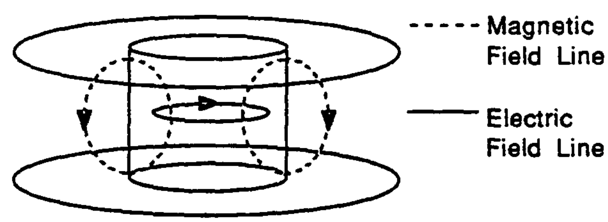

Figure 3 Field Configuration for the TE011 Resonant Mode

To determine microwave surface resistance of the plates (or one plate), the Q factor of the structure must be measured. Relative measurements of the resistance can be accomplished quite easily by simple determination of the Q factor ratio for copper and the sample under test, for example a high Tc superconductor plate. For measurements of absolute values of resistance we should note, that for this particular structure

$$1/Q_{total} = 1/Qd + 1/Qtop1 + 1/Qtop2 + 1/Qbottom1 + 1/Qbottom2 + 1/Qr$$

where : $Qd = 1/\tan\delta$ - the dielectric quality factor
Qr - the radiation quality factor- which in this case can be omitted
Qtop1/Qbottom1 - the quality factor corresponding to losses in conductive plates directly under the high dielectric - top/bottom respectively
Qtop2/Qbottom2 - the quality factor corresponding to losses in conductive plates outside the dielectric - top/bottom respectively.

It can be shown that for high dielectric constant materials (typically ranging from 80 for lower frequency resonators to 25 for higher frequency resonators), 90-95 % of losses occur in the plates directly under the high dielectric constant material. In addition, typical dielectric materials used are very low loss especially at cryogenic temperatures, which gives the method high sensitivity. The effect of loss tangent can be also calibrated out using the method described in [6], utilizing two dielectric resonators manufactured from the same lot of material; one operating in the TE011 mode, the second in a higher, for example TE012, mode.

The formulas for resistance calculations from measured Q factor values are given below. Since the fixture (probe) can be characterized for tanδ (dielectric resonator) and surface resistance (copper) at any given temperature, the only unknown will be the surface resistance of the sample (superconductor) under test. Therefore we have:

$$Rsmeas = (A/Qtotal - \tan\delta) / B - R_{sfixt}$$

where [6];

$$A = 1 + W/\varepsilon \qquad B = (\lambda_o / 2L)^3 * (1+W)/(60\pi^2\varepsilon)$$

$$W = \frac{J1^2(\xi)\,[K0(\zeta)K2(\zeta) - K1^2(\zeta)]}{K1^2(\zeta)\,\,[J1^2(\xi) - J0(\xi)J2(\xi)]}$$

and,
Rsmeas - surface resistance of the sample
Rsfixt - surface resistance of the fixture
L - length of the dielectric resonator
ε - dielectric constant
λ_o - wavelength
J0, J1, J2, K0, K1, K2 - regular and modified Bessel functions

$$\xi^2 = (2\pi/\lambda_o)^2 - (\pi/L)^2$$

$$\zeta^2 = (\pi/L)^2 - (2\pi/\lambda_o)^2$$

EXPERIMENTAL RESULTS

The developed dielectric resonator probe, shown in Figure 5, was used to determine microwave surface resistance of bulk high Tc superconductors such as Y-Ba-Cu-O and *Bi-Sr-Ca-Cu-O*. The results are listed in Figure 6. At the present time, additional samples of thin film superconductors are undergoing similar evaluation. We should note that due to the high dielectric constant of dielectric resonator materials, the surface area of the samples needed for measurements is quite small, for example less than 0.2 cm^2 at 10 GHz. This would enable us to probe larger samples of materials, when available, and locate areas with the best microwave properties.

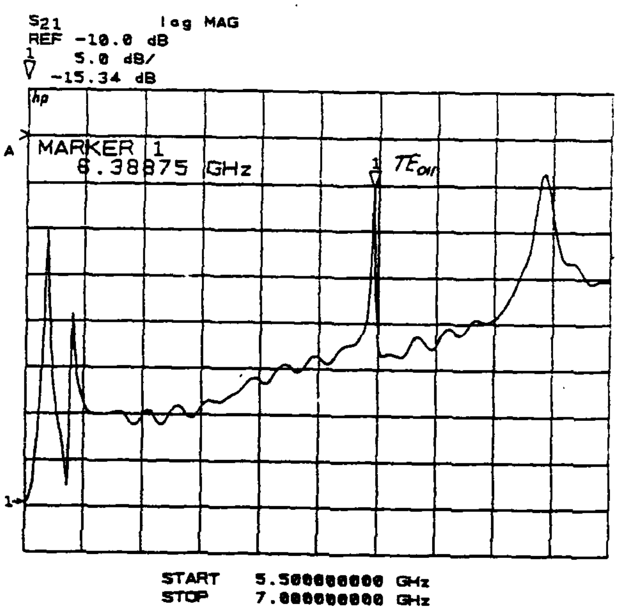

Figure 4 Typical Resonant Modes of the Dielectric Resonator Probe

CONCLUSIONS

A modification of a well established method for dielectric materials measurements was shown to have excellent potential as a production type, nondestructive test method for high Tc superconductors in bulk and thin film forms. A proposed test fixture configuration can serve as a dielectric resonator probe for large superconductor samples. At the same time, relatively small samples can be measured at lower microwave frequencies where accuracy of measurements is highest. The fixtures are easy to make and use. Analytical solutions to the electromagnetic field problem of the structure are available, and necessary computer programs were written. This facilitates discussion of error estimation of measured values, calibration and resistance calculations.

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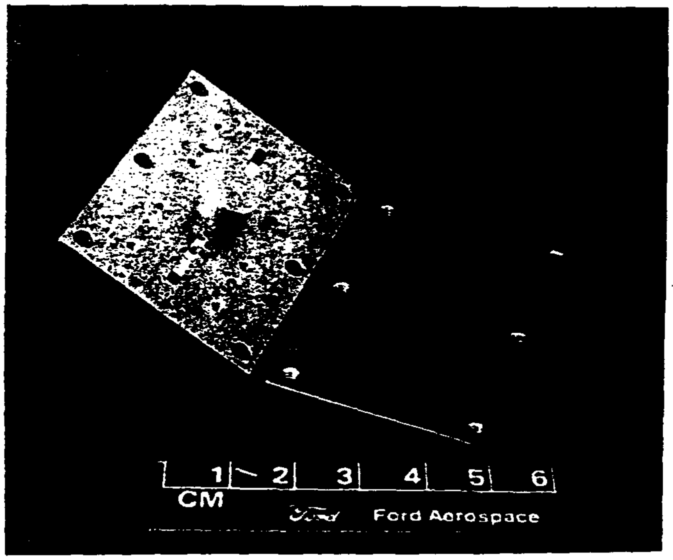

Figure 5 Dielectric Resonator Probe for 6.5 GHz Measurements

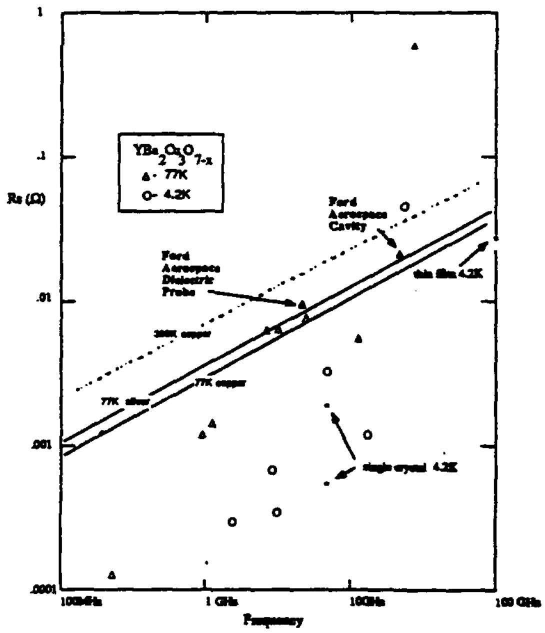

Figure 6 Microwave Surface Resistance of High Tc Superconductors
(Modification of graph presented at 1988 IEEE Symposium workshop on Superconductivity and Microwaves)

APPENDIX B

AN IMPROVED SENSITIVITY CONFIGURATION FOR THE DIELECTRIC PROBE TECHNIQUE OF MEASURING MICROWAVE SURFACE RESISTANCE OF SUPERCONDUCTORS

An Improved Sensitivity Configuration for the Dielectric Probe Technique of Measuring Microwave Surface Resistance of Superconductors

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ABSTRACT

The measurement of the microwave properties of HTSC materials, both bulk and thin film, is very important to the potential users of these materials. Several techniques have been developed for the measurement of HTSC microwave surface resistance including cavity end wall replacement, disc resonator, and resonant transmission line structures. The post dielectric resonator used as a probe offers a simple technique for measuring the microwave surface resistance of superconductors. Advantages of this technique include its simplicity and the ability to measure superconductor samples of small surface area, or nondestructively measure selected areas of larger samples. A new physical configuration for the dielectric probe which offers improved sensitivity is described, and selected measurement results are given.

1. INTRODUCTION

Since the discovery of high temperature superconductivity in 1987, there has been considerable effort focused toward developing the microwave applications of high temperature superconductors (HTSC). In conjunction with this effort, several techniques have been proposed and developed for evaluating the microwave surface resistance (R_S) of superconductors. Many of these methods have been successfully used to evaluate microwave performance of superconductors, however, all of them suffer from certain drawbacks. The dielectric resonator probe measurement technique offers a number of attractive advantages over other measurement techniques, particularly as a simple, quick, reliable method of screening superconductor samples for microwave applications.

In this paper, we will present a brief overview of some of the more popular microwave surface resistance measurement techniques along with some of their properties. We will also discuss the desirable characteristics of an R_S measurement method used for HTSC materials. Next, we will present the dielectric probe in an improved sensitivity configuration as an alternative measurement technique and discuss its advantages over the other methods. Some measurement results will also be presented.

2. OVERVIEW OF POPULAR MICROWAVE SURFACE RESISTANCE MEASUREMENT TECHNIQUES

Nearly all of the methods used to evaluate the microwave properties of superconductors involve measuring the quality factor (Q) of some resonant microwave structure which in some way incorporates the superconductor sample under test. The more popular microwave surface resistance measurement techniques include cavity end cap replacement, cavity perturbation, parallel plate resonator, and a variety of resonant microstrip structures. Some properties of these techniques are briefly discussed below.

2.1 TE011 Mode Cavity End Cap Replacement

In the cavity end cap method, one of the end caps of a TE011 mode resonant cavity is replaced by the superconductor test sample. The contribution of the superconducting end cap to the measured cavity Q can easily be calculated to determine the surface resistance of the sample. This method is illustrated in Figure 1, and a cavity end cap test fixture is shown in Figure 2. This measurement technique is successfully used to measure microwave surface resistance at a number of laboratories, however, it does

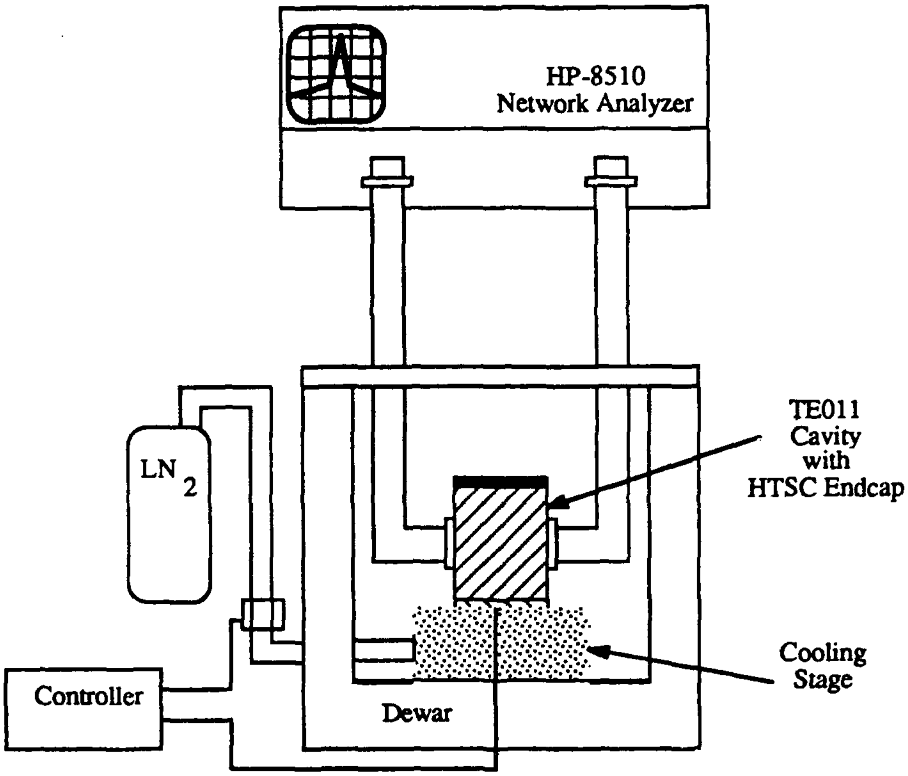


Figure 1 Measurement set-up for the TE011 mode cavity end wall replacement technique.

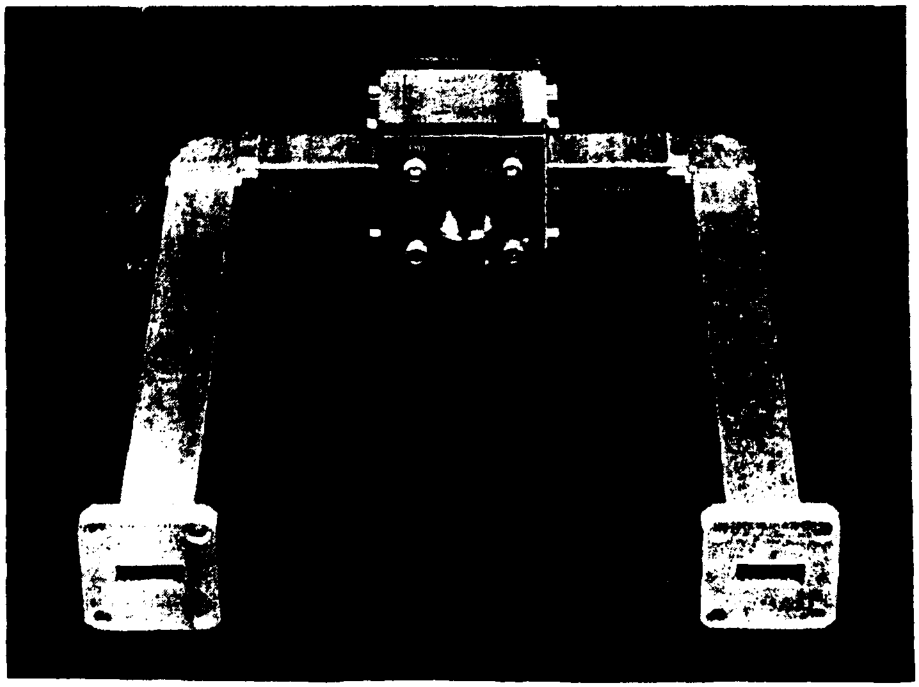


Figure 2 Test fixture for cavity end wall replacement measurements at 20 GHz.

have a few drawbacks. The most serious drawback is that it requires test samples of relatively large surface area to make measurements at lower microwave frequencies (greater than 5 cm^2 for frequencies below 20 GHz) where the materials are most likely to be used and where Q measurements are easier to make. Also, the sensitivity and accuracy of the measurements are decreased since the losses in the metal cavity dominate the Q value, particularly for measurements above the critical temperatures of low temperature superconductors. Cavities made from HTSC materials may be an option for increased sensitivity at higher temperatures in the future, but are currently not practical because of the relatively poor microwave performance of bulk materials.

2.2 Disk or Parallel Plate Resonator Method

The disk or parallel plate resonator technique proposed by Belohoubek et. al. [1] and used by Taber [2] incorporates two parallel plates or disks of superconductor separated by a thin dielectric spacer as shown in Figure 3. An average surface resistance value for the two test samples can be calculated from the measured Q. One drawback of this technique is that the measured R_s value is an average of two samples. This is a particular problem when measuring at higher temperatures where niobium can't be used for one of the plates of the resonator. A second drawback is that it is limited to one specific sample size and geometry for a given test fixture.

2.3 Cavity Perturbation Techniques

A variety of cavity perturbation techniques have been proposed and are being used for R_s measurements. These involve incorporating the superconductor test sample within a resonant cavity such that it perturbs the cavity field distribution in a way that its contribution to the cavity Q can be calculated. An example of this method is illustrated in Figure 4 [3]. Perturbation techniques typically require very small test samples and suffer from decreased sensitivity at temperatures where niobium cavities can't be used.

Disk/ Parallel Plate Resonator Measurement Technique

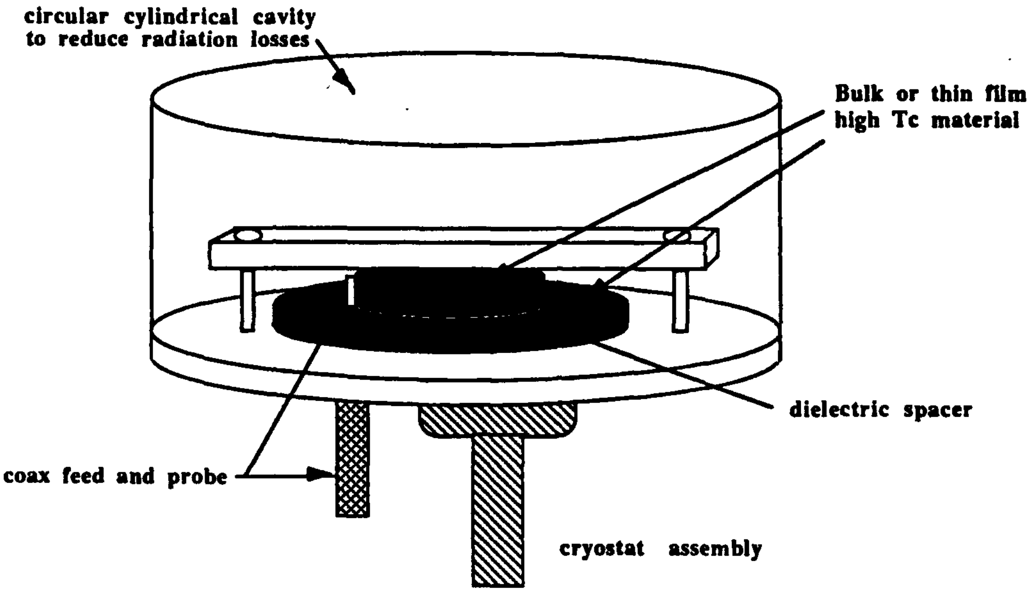


Figure 3 Illustration of the measurement set-up for the disk resonator technique. Taber later modified this technique in the parallel plate resonator [1,2].

Cavity Perturbation Technique

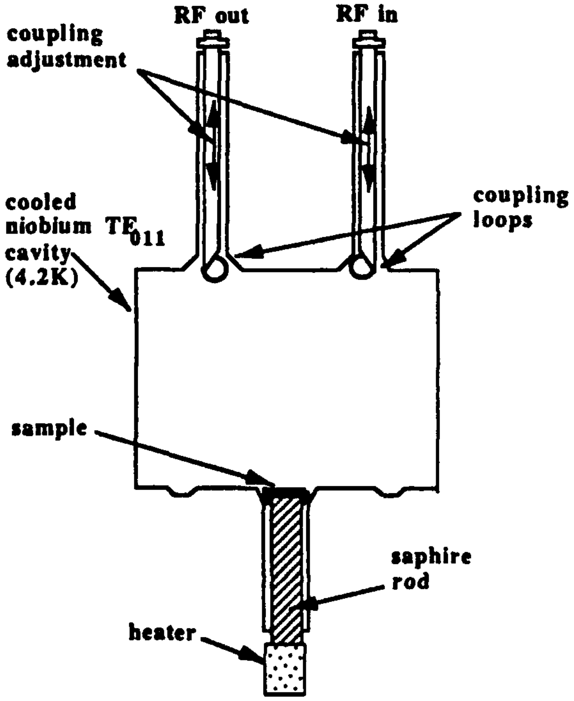


Figure 4 Illustration of the cavity perturbation technique from Moffat et. al. [3]. The sample temperature is controlled independently from the cavity temperature which is at 4.2K.

2.4 Resonant Microstrip Structures

Another technique for evaluating the microwave properties of superconductors is to measure the Q value of resonant structures of superconducting microstrip transmission line. A wide variety of transmission line structures have been used including ring resonators and meanderlines [4,5]. Figure 5 illustrates two of these structures [5,6]. This technique has distinct advantages over other methods since it measures the film properties on the substrate side of the film, and the measurements are made on structures that closely resemble the actual usage of the films in many microwave applications. However, microstrip measurement techniques have drawbacks in that they measure only a small portion of the film surface, they are limited to a specific film size for a given test fixture and pattern, and most importantly, the films can't be used for any other purpose after being tested.

3.0 CHARACTERISTICS OF A GOOD MICROWAVE SURFACE RESISTANCE MEASUREMENT TECHNIQUE

All of the measurement techniques outlined above have desirable characteristics, yet they also have important drawbacks. The desirable characteristics for a good R_S measurement technique include the following.

- Accuracy, Repeatability, Sensitivity
- Simplicity, and ability to perform measurements quickly
- Ability to use the sample after testing (nondestructive)
- Ability to test small samples and flexibility in sample dimensions
- Ability to test at more than one frequency and at reasonably low frequencies
- Maintained sensitivity at temperatures above low T_C

Each of the measurement methods outlined in the previous section has many of these characteristics, but none of them has all of these properties. In this paper, the dielectric resonator probe in

Microstrip Resonator Techniques

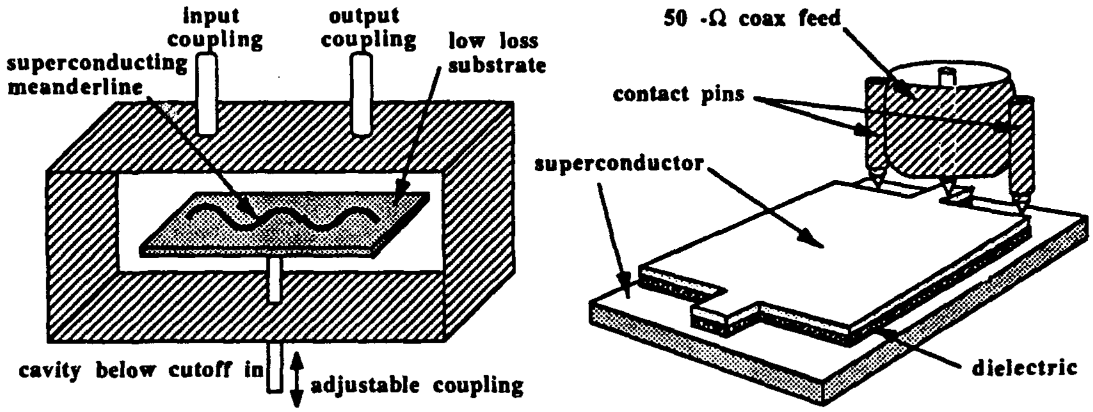


Figure 5 An illustration of two types of resonant microstrip structures used for HTSC Rs measurements [5,6]. A variety of other microstrip patterns are also used.

Dielectric Probe Technique

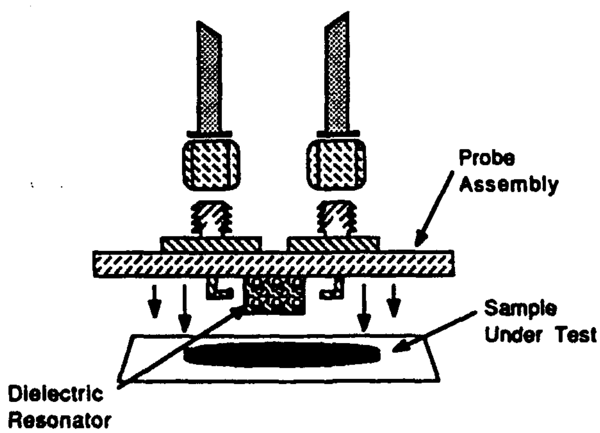


Figure 6 Illustration of the post resonator configuration for the dielectric probe. An improved sensitivity configuration for the probe is shown in Figures 12 and 13.

an improved sensitivity configuration is presented as an alternative for measuring the microwave surface resistance of high temperature superconductors.

4.0 THE DIELECTRIC RESONATOR PROBE TECHNIQUE

The dielectric resonator probe measurement technique is an adaptation of a well known technique for measuring the loss tangents of dielectric resonator materials given that the surface resistance of nearby conductors is known [7,8]. However, in the dielectric probe case, the loss tangent of the dielectric resonator is known and the conductivity of the nearby superconductor is unknown. The general configuration of the dielectric probe is illustrated in Figures 6 and 7 [7]. In these figures, a weakly coupled circular dielectric resonator is sandwiched between two conductive plates, one of these plates being the superconductor sample under test. As in the case of the other measurement techniques discussed in this paper, R_S is calculated from a measured Q value. The TE011 mode is used for measurements since it is easily identified, relatively insensitive to small gaps between the dielectric and the test sample, and has no axial currents across any possible discontinuities in the fixture (similar to the TE011 mode used in the metal cavity end cap replacement technique). The field configuration for the TE011 mode is illustrated in Figure 8.

4.1 Calculation of Absolute Rs Values From Measured Q Values

For the structure of Figures 6 and 7, the absolute surface resistance of a sample under test can be calculated from a measured Q value using the formulas below after substituting the known values for the dielectric loss tangent and the surface resistance of the copper fixture [7].

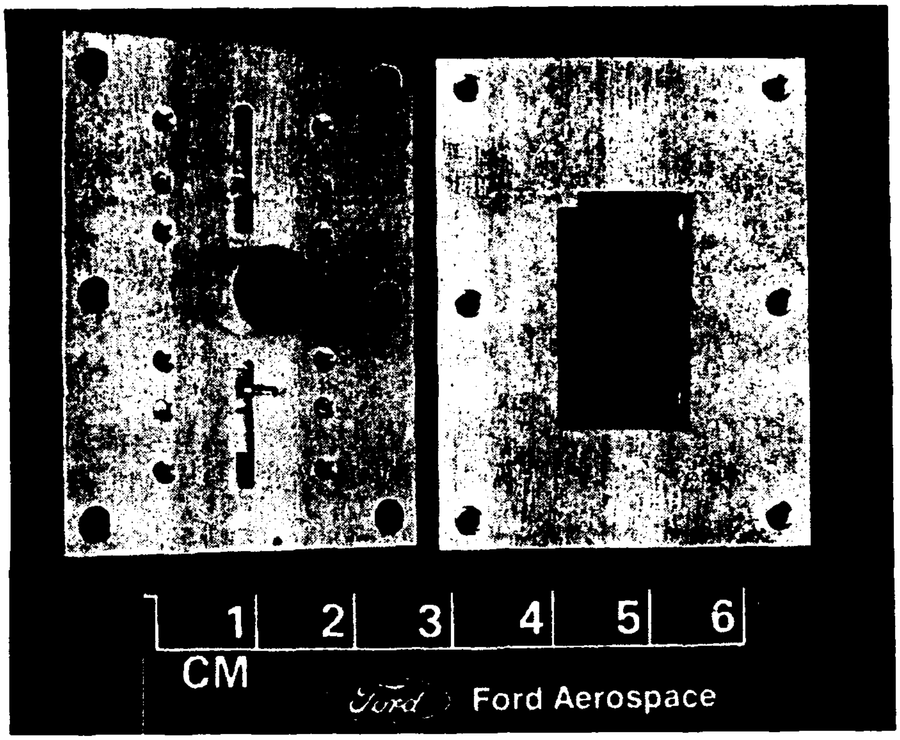


Figure 7 Photograph of the dielectric probe in the post configuration. The dielectric resonator is sandwiched between two conductive plates. Energy is coupled to and from the resonator using the coupling probes shown [7].

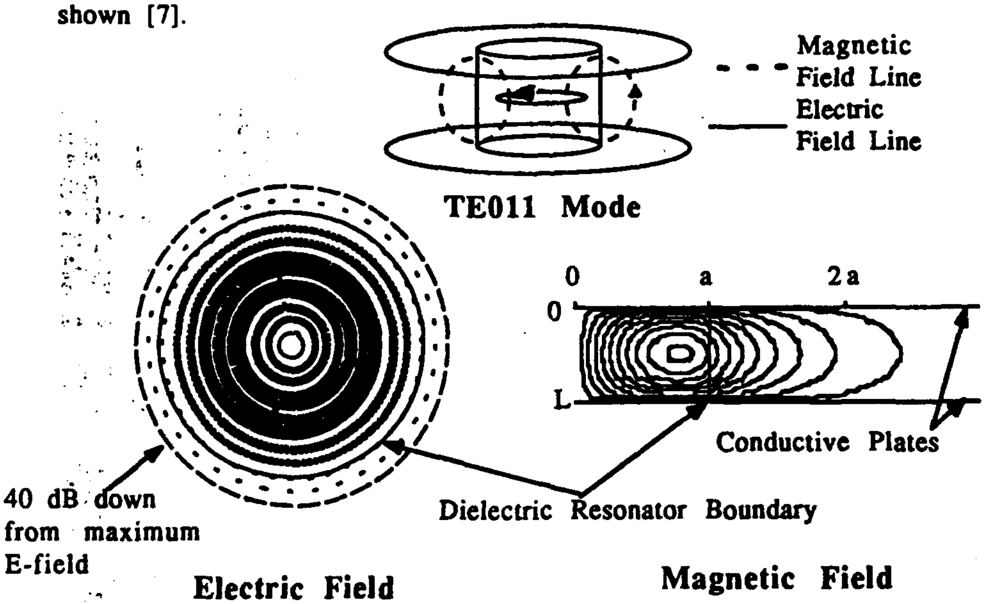


Figure 8 Illustrations of the field configurations in the dielectric probe. The top drawing shows the general TE011 mode configuration. The bottom two drawings are computer generated plots of the electric and magnetic fields stored within the resonant circuit. These plots illustrate the confinement within the resonator.

$$R_{smeas} = (A/Q_{meas} - \tan\delta)/B - R_{sfixt}$$

where [9];

$$A = 1 + W/\varepsilon, \qquad B = (\lambda_o/2L)^3 * (1 + W)/(60\pi^2\varepsilon)$$

$$W = \frac{J1^2(\zeta)\,[K0(\zeta)K^2(\zeta) - K1^2(\zeta)]}{K1^2(\zeta)\,[J1^2(\zeta) - J0(\zeta)J2(\zeta)]}$$

and,

R_{meas} - surface resistance of the sample
R_{sfixt} - surface resistance of the fixture
L - length of the dielectric resonator
$\tan\delta$ - loss tangent of the dielectric resonator
ε - dielectric constant of the dielectric resonator
λ_o - wavelength of measurement
Jo, J1, J2, K0, K1, K2, - regular and modified Bessel functions

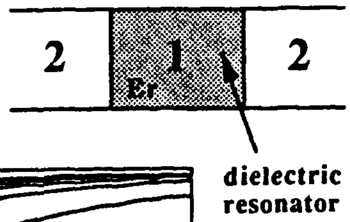
$$\zeta^2 = (2\pi/\lambda_o)^2 - (\pi/L)^2$$

$$\zeta^2 = (\pi/L)^2 - (2\pi/\lambda_o)^2$$

A key to the sensitivity of the dielectric probe technique is that the electric and magnetic fields of the resonant circuit are largely confined within the low loss, high dielectric constant material. Hence, the measured Q value is determined largely by the losses from the portion of the conductive plates directly under the dielectric resonator. The computer generated plots in Figure 8 illustrate this field confinement for one particular dielectric probe configuration. The filling factor which is defined as the ratio of the energy stored within the dielectric material to the total energy stored in the circuit is plotted in Figure 9 for a variety of dielectric resonators. The filling factor shows the extent to which the measured Q value is determined by the conductivity of the end plates directly under the resonator and is indirectly a measure of the probe sensitivity. Figure 9 illustrates that over 95% of the stored energy is within the dielectric resonator region for most

Filling Factor Plot

$$P = \frac{\text{Energy Stored in Region1}}{\text{Total Energy Stored}}$$



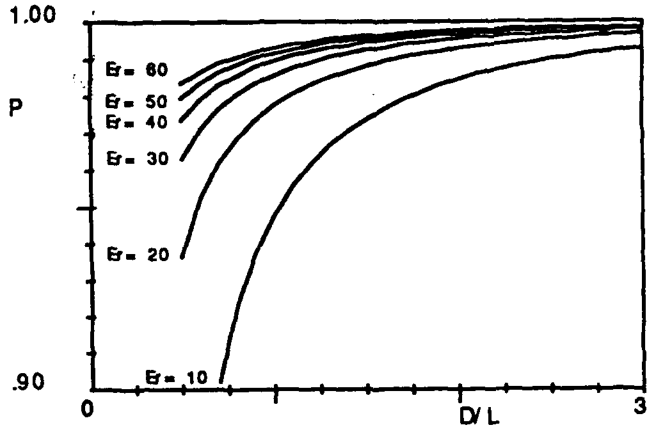


Figure 9 Plot of filling factor verses diameter to length ratio for dielectric resonators with various permitivities. Filling factor is indirectly a measure of dielectric probe sensitivity.

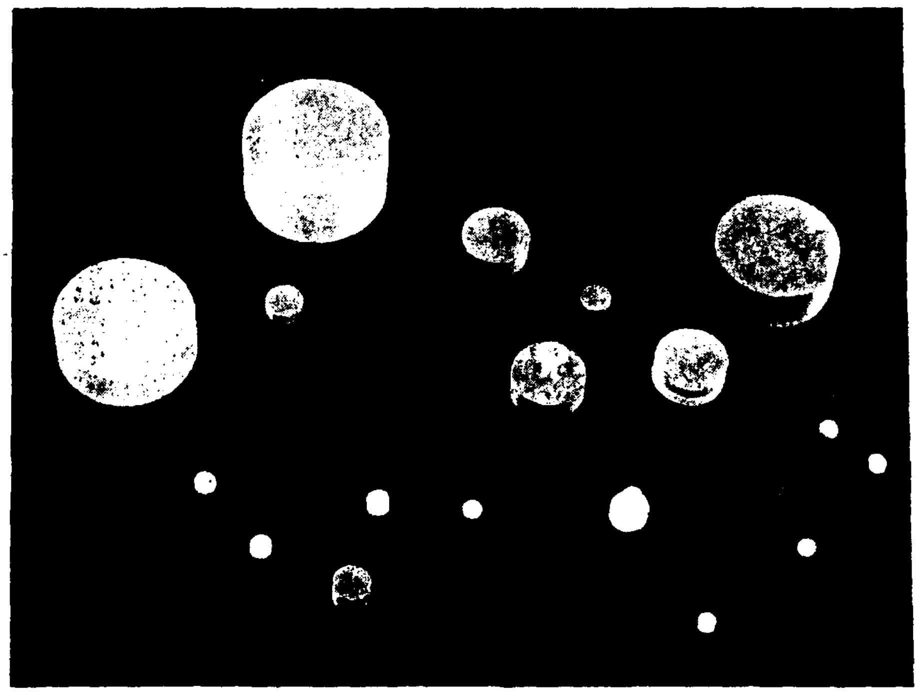


Figure 10 Photograph of dielectric resonators similar to those used in the dielectric probe. The variety of dielectric resonators available adds the advantage of frequency flexibility to a given probe fixture.

practical probe configurations. Hence, over 95% of the conductor losses contributing to the measured Q are from the portion of the conductors directly under the ends of the dielectric resonator.

4.2 Properties of the Dielectric Resonators Used

Since the dielectric resonator is the central element in the dielectric probe fixture, its properties largely determine the performance of the measurement technique. Dielectric resonators made from a variety of materials with relative dielectric constants between 25 and 80 are commonly available in a number of standard sizes. A variety of these are shown in Figure 10. The small resonator size for a given resonant frequency, the high degree of field confinement as illustrated in Figure 8, and the high Q performance of these resonators, particularly at cryogenic temperatures where measurements are performed, are key elements to the dielectric probe approach.

Since most of the energy is stored within the dielectric resonator, the losses from the dielectric material must be extremely small compared to the losses from the test sample in order to ensure a sensitive measurement. Figure 11 is a plot of the unloaded Q of a dielectric resonator verses temperature [10]. At 77K where R_s measurements are commonly made, unloaded dielectric resonator Q values of over 100,000 are common. This extremely low loss performance ensures high sensitivity for dielectric probe measurements at 77K.

An additional benefit to the dielectric probe technique can be derived from the variety of high Q dielectric materials available. This variety makes it possible to make measurements at a number of different frequencies with the same test fixture simply by interchanging the dielectric resonator with a new resonator of the same dimensions but having a different dielectric constant. Measurements at selected frequencies over a broad band are possible from this option.

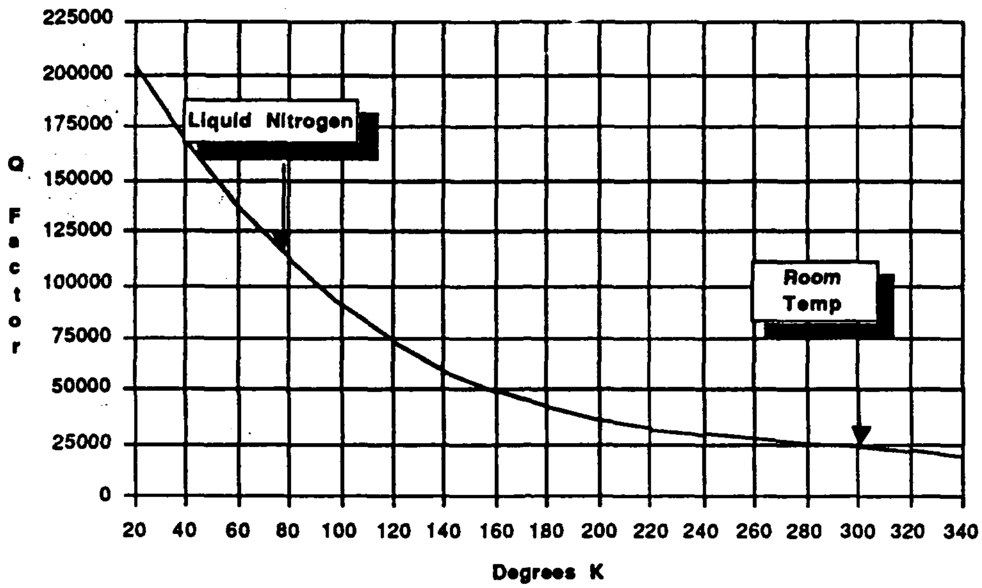


Figure 11 Plot of dielectric resonator unloaded quality factor verses temperature for a selected dielectric resonator. This high Q performance is a key to the sensitivity of the dielectric probe measurement technique.

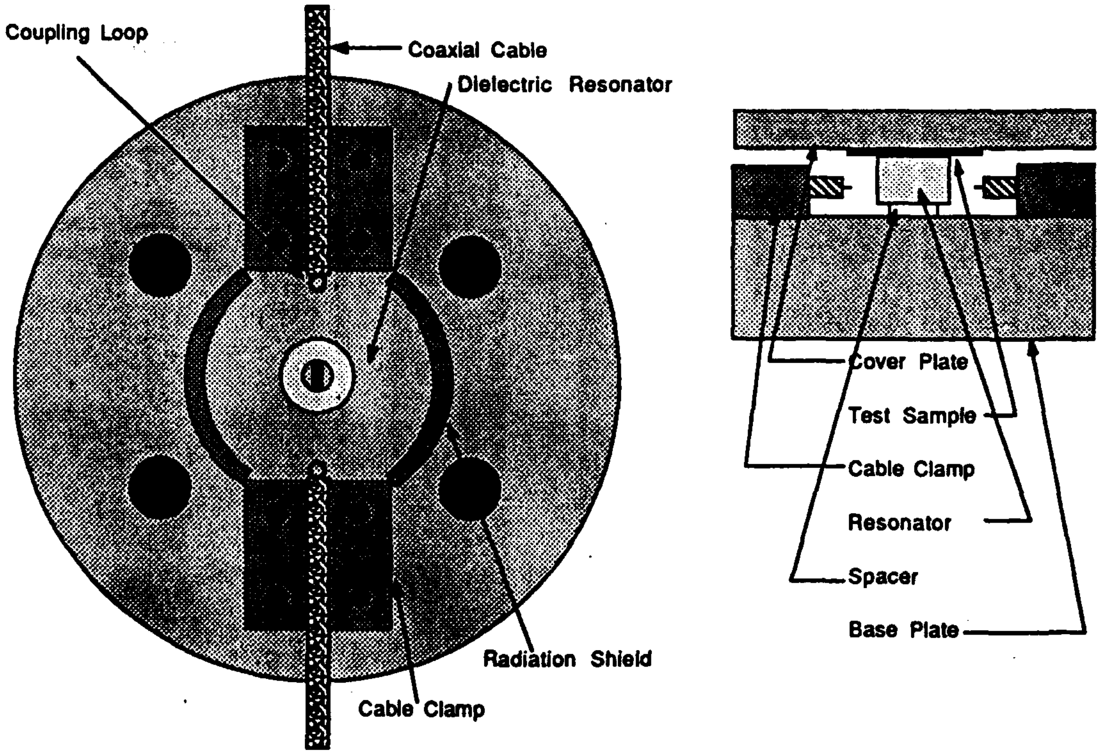


Figure 12 Drawings of the improved sensitivity configuration for the dielectric probe. Top view left, and cross sectional view right.

4.3 Improved Sensitivity Configuration for the Dielectric Probe

The dielectric probe configuration illustrated in Figures 6 and 7 employs a dielectric resonator sandwiched between two conductive metal plates in a post resonator configuration. As discussed earlier, the measured Q from this configuration is dominated by the losses from the conductive plates directly above and below the dielectric resonator. In this configuration, the Q value is determined by the combination of the test sample at one end of the dielectric resonator and the copper plate at the opposite end of the resonator. The improved sensitivity configuration for the probe shown in Figure 12 alleviates this problem by separating the dielectric resonator from the copper plate using a low loss plastic spacer. The physical separation of the probe from the copper plate significantly decreases the contribution of the copper to the measured Q. In this configuration, the dielectric probe maintains the advantages of the post resonator configuration, but has the advantage of significantly increased sensitivity. Figure 13 is a photograph of an improved sensitivity dielectric probe test fixture.

4.4 Analysis of Dielectric Probe Q Measurements

Absolute R_S values from dielectric probe measurements can be calculated by the technique discussed earlier, but for most measurement purposes absolute R_S values are not required, and measurements relative to a common standard are sufficient. The dielectric probe represents a fast and simple method to determine the surface resistance of HTSC samples relative to a copper or other normal metal standard. The measured Q value is determined by contributions from the following components as illustrated in Figure 14.

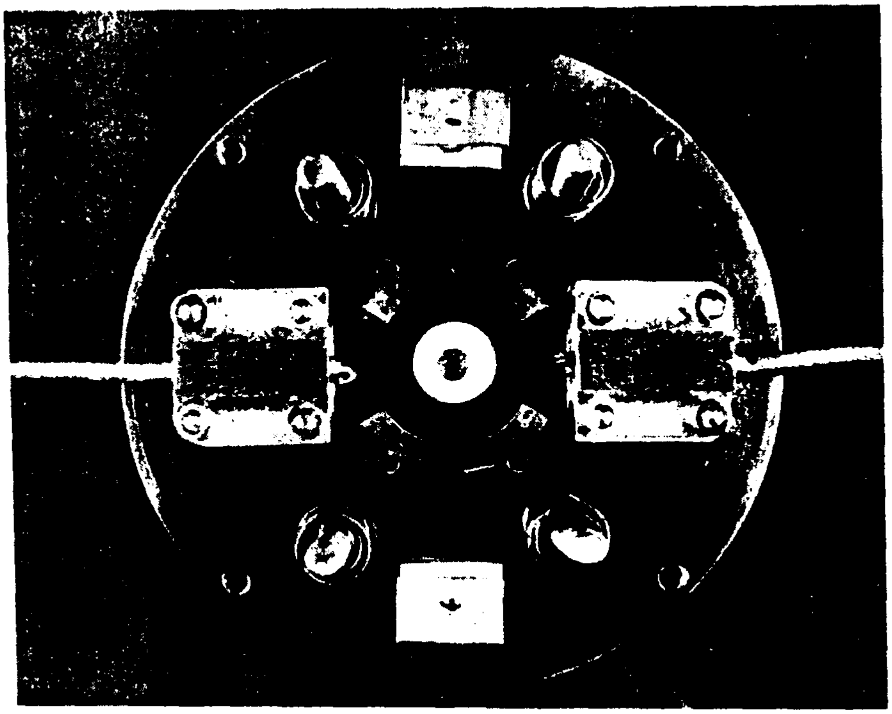


Figure 13 Photogragh of the dielectric resonator probe in the improved sensitivity configuration.

$$\frac{1}{Q_m} = \frac{1}{Q_d} + \frac{1}{Q_{t\,1}} + \frac{1}{Q_{t\,2}} + \frac{1}{Q_b} + \frac{1}{Q_r} + \frac{1}{Q_s}$$

$$\frac{1}{Q_{t\,1}} = \frac{1}{Q_m} - \frac{1}{Q_{fix}}$$

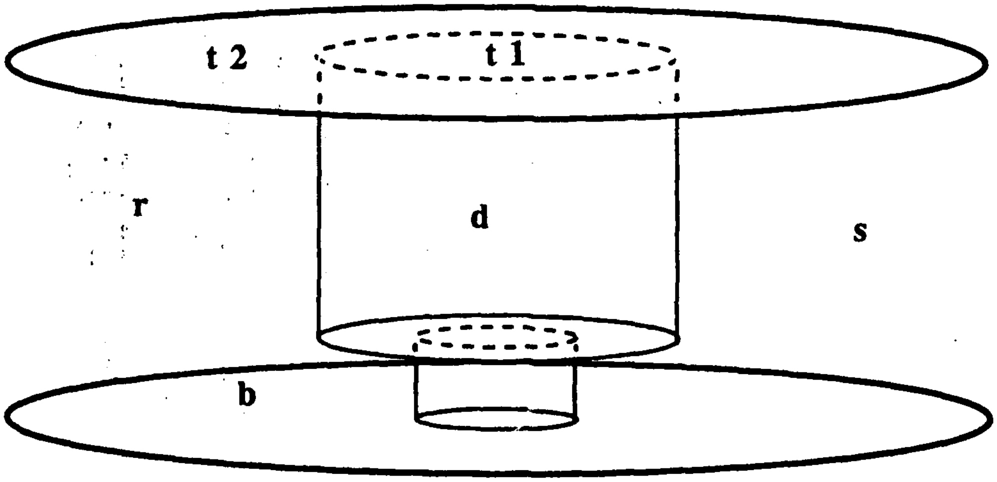


Figure 14 Illustration of the improved sensitivity configuration of the dielectric probe showing contributions to the measured Q value.

$$1/Q_m = 1/Q_d + 1/Q_{t1} + 1/Q_{t2} + 1/Q_b + 1/Q_r + 1/Q_s$$

where; Q_m - measured quality factor

Q_d - Q contribution from the dielectric and spacer combined

Q_{t1} - Q contribution from the test sample

Q_{t2} - Q contribution from the top plate excluding the test sample

Q_b - Q contribution from the bottom plate

Q_r - Q contribution from radiation losses

Q_s - Q contribution from the side walls

By defining Q_{fix} as the Q of the fixture excluding the test sample and solving for Q_{t1}, the Q of the test sample, we get

$$1/Q_{t1} = 1/Q_m - 1/Q_{fix}$$

By measuring Q_m for two samples of known conductivity, gold and copper for example, and substituting into the above equation, we get a value for Q_{fix}. Once Q_{fix}, the Q contribution of the fixture, is established, R_s measurements relative to the copper and gold calibration pieces can easily be calculated from the above equation.

4.5 Measured Results Using the Dielectric Probe

The dielectric resonator probe shown in Figure 13 has been used to measure over 60 HTSC thin film samples from a variety of sources. Measurements have been found to be repeatable, fast, simple to perform, and accurate. The best films measured have had R_s values less than 1/20th that of copper, and there is no indication that this is near the limit of the fixture sensitivity. Figures 15 through 18 show measured results from the dielectric probe. Figure 15 shows a relatively broad band view of the frequency response of the probe illustrating the easily identified TE011 resonant mode. Figure 16 shows the response of the probe with a YBCO test sample at both room temperature and at 77K. Figure 17 shows the response of the probe with a copper calibration sample,

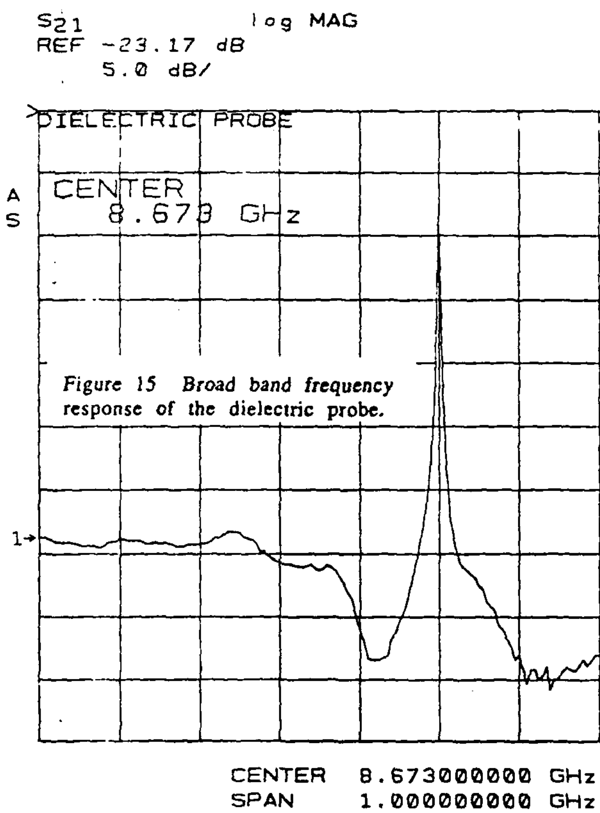


Figure 15 Broad band frequency response of the dielectric probe.

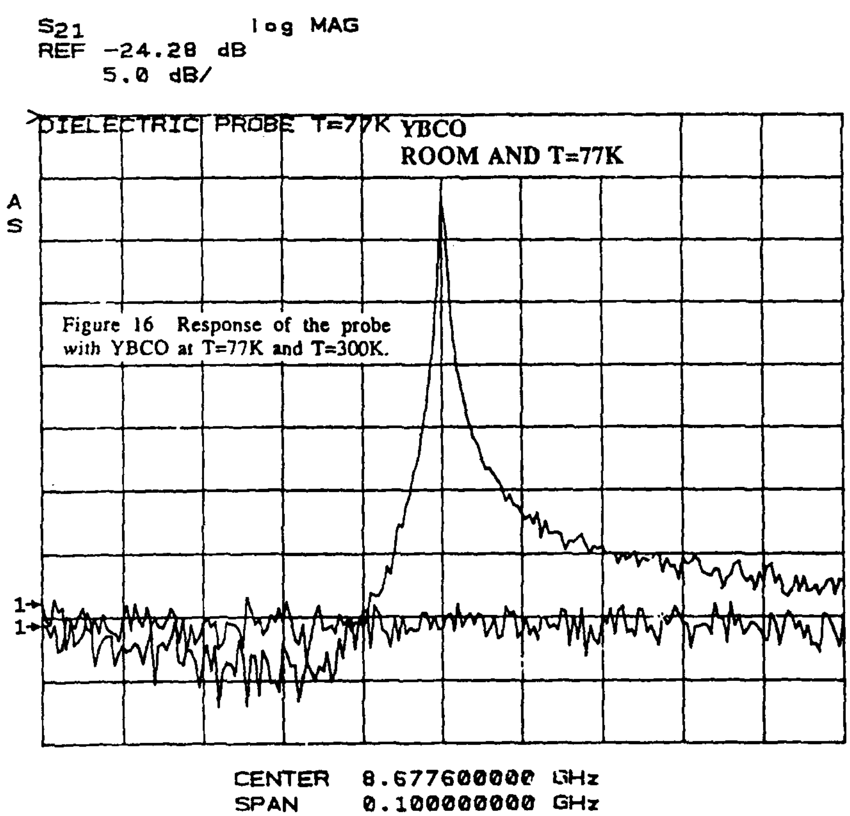


Figure 16 Response of the probe with YBCO at T=77K and T=300K.

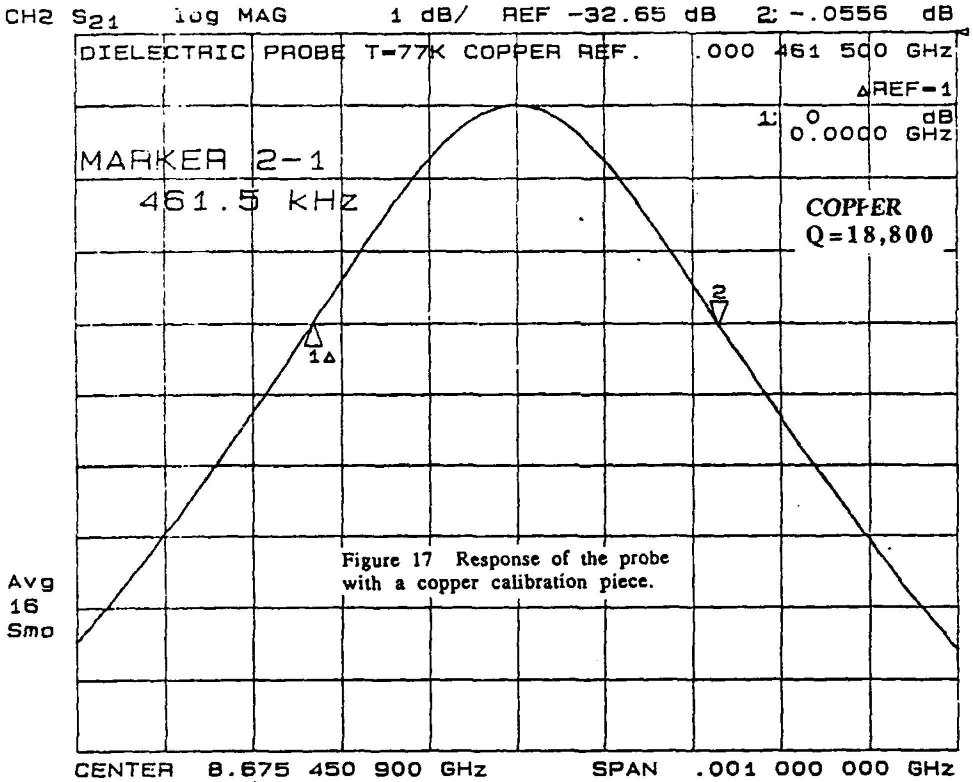


Figure 17 Response of the probe with a copper calibration piece.

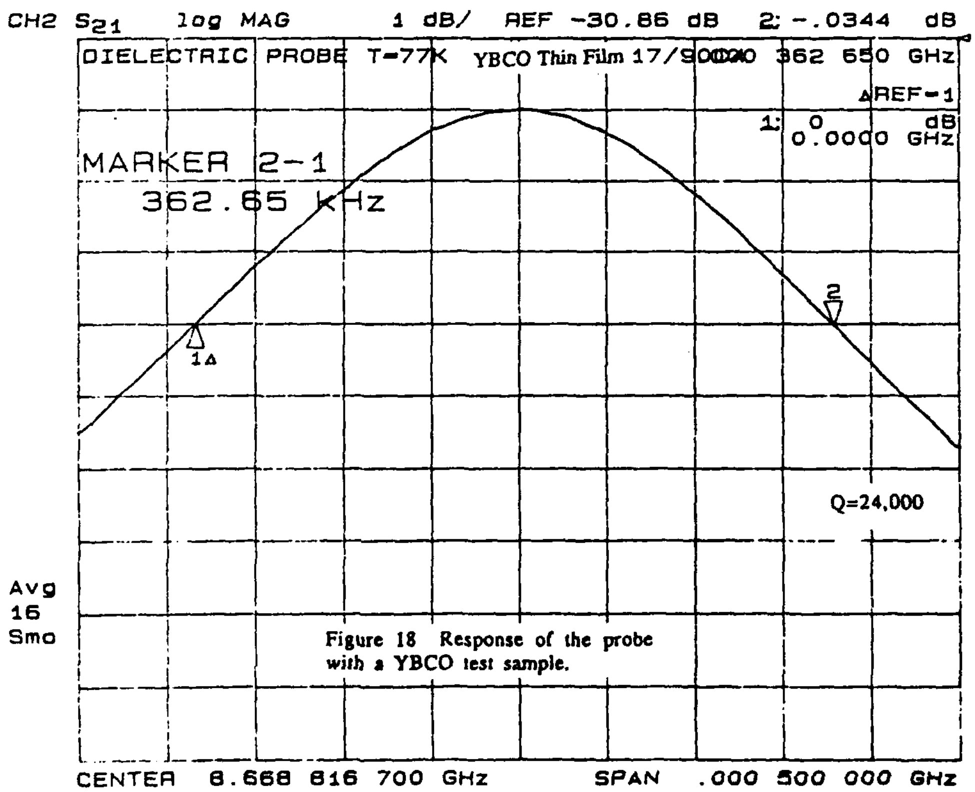


Figure 18 Response of the probe with a YBCO test sample.

and Figure 18 shows the superior response of the probe with a YBCO test sample.

5. CONCLUSIONS

Although there are currently a number of alternative techniques available for measuring the microwave surface resistance of high temperature superconductors, the dielectric probe is an attractive measurement technique, particularly as a quick, simple means of screening HTSC samples for microwave applications. Some of the properties of the improved sensitivity configuration of the dielectric resonator probe technique include the following.

- Accuracy, Sensitivity, and Repeatability
- Ability to measure small samples at reasonably low microwave frequencies or to nondestructively measure selected areas of larger samples
- Ability to measure at more than one frequency with the same test fixture
- Simple to perform tests quickly
- Maintained sensitivity at temperatures above T_C
- Ability to obtain either absolute or relative R_S values
- Ability to measure either bulk or thin film samples.

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APPENDIX C

US PATENT # 5,105,158
DIELECTRIC MICROWAVE RESONATOR PROBE

US005105158A

United States Patent [19]

Fiedziuszko et al.

[11] **Patent Number: 5,105,158**

[45] **Date of Patent: Apr. 14, 1992**

[54] **DIELECTRIC MICROWAVE RESONATOR PROBE**

[75] Inventors: **Slawomir J. Fiedziuszko; Peter D. Heidmann**, both of Palo Alto, Calif.

[73] Assignee: **Space Systems/Loral, Inc.**, Palo Alto, Calif.

[21] Appl. No.: **479,509**

[22] Filed: **Feb. 13, 1990**

[51] **Int. Cl.**^{5} **G01R 27/00**; H01P 7/10

[52] **U.S. Cl.** **324/693**; 324/708; 333/219.1

[58] **Field of Search** 324/629, 633, 636, 637, 324/691, 693, 708, 71.6, 653, 632; 333/219.1

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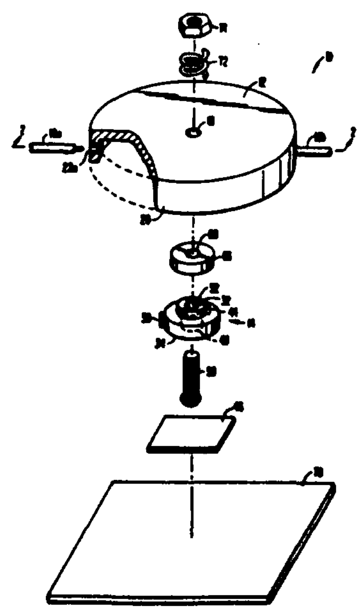
Primary Examiner—Kenneth A. Wieder

Attorney, Agent, or Firm—Townsend and Townsend

[57] **ABSTRACT**

A dielectric resonator probe for measuring surface resistance of a test material, particularly at cryogenic temperature, is provided. A dielectric resonator is mounted near to but spaced from a conductive plate and is positioned in contact with a test material. Preferably, a low-loss dielectric spacer separates the resonator from the upper plate. The dielectric resonator has a larger lower surface area than upper surface area. The dielectric resonator includes a hole therethrough for increasing mode separation and for accommodating a mounting bolt. The mounting bolt is preferaoly nonconductive and is coupled to a spring for resiliently mounting the resonator and spacer to the plate so as to accommodate differential thermal expansion of the components.

28 Claims, 3 Drawing Sheets



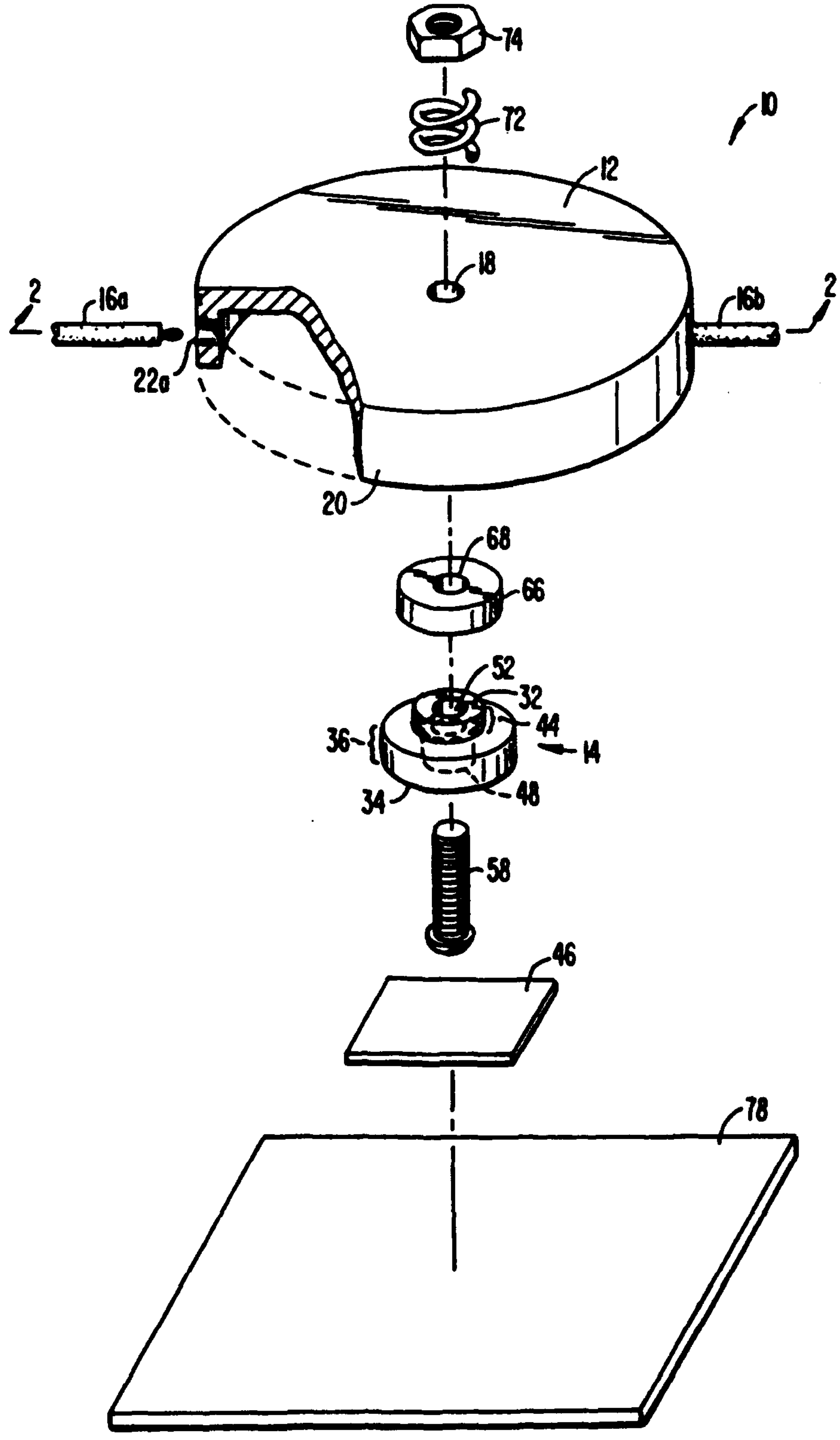
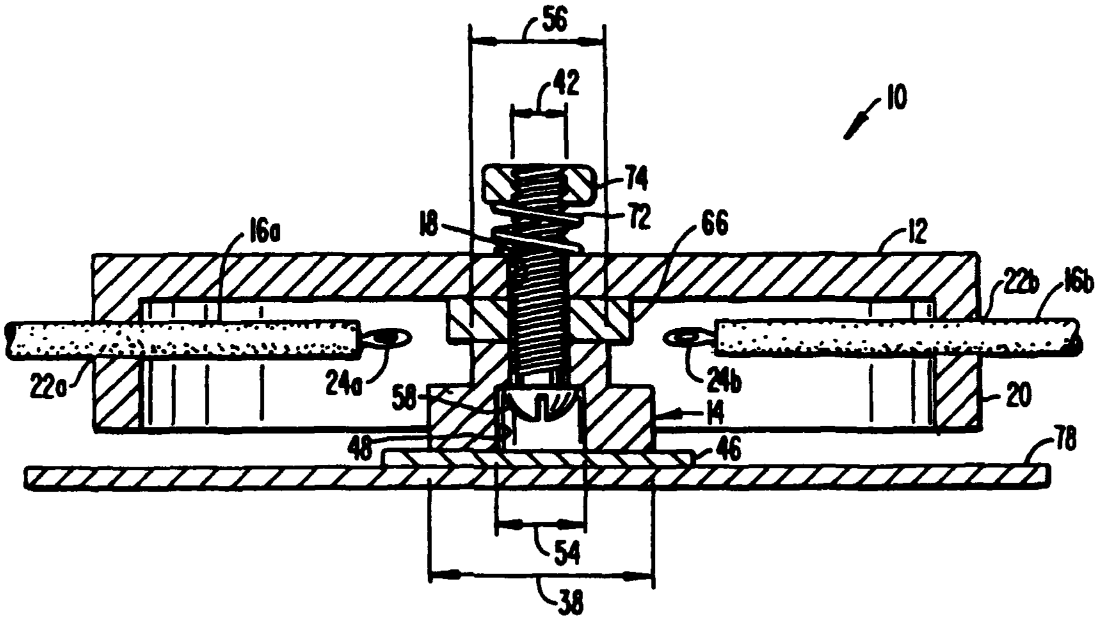
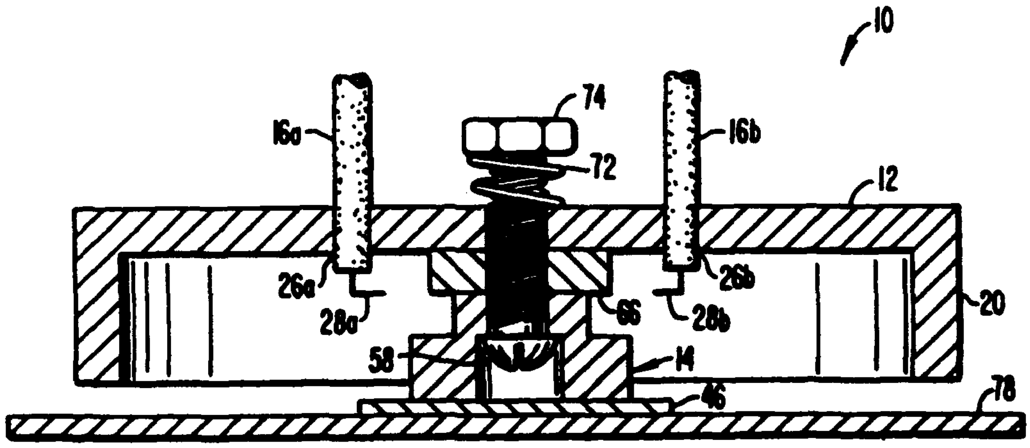


FIG._1.



56
42
10
74
72
18
66
12
16a
22b
16b
22a
24a
24b
58
14
20
48
46
78
54
38

FIG._2.



10
74
16a
16b
72
12
26a
26b
28a
66
28b
20
58
14
46
78

FIG._3.

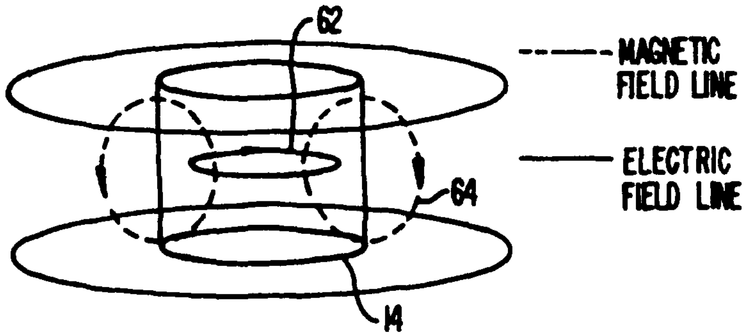

62
MAGNETIC FIELD LINE
ELECTRIC FIELD LINE
64
14

FIG._4.

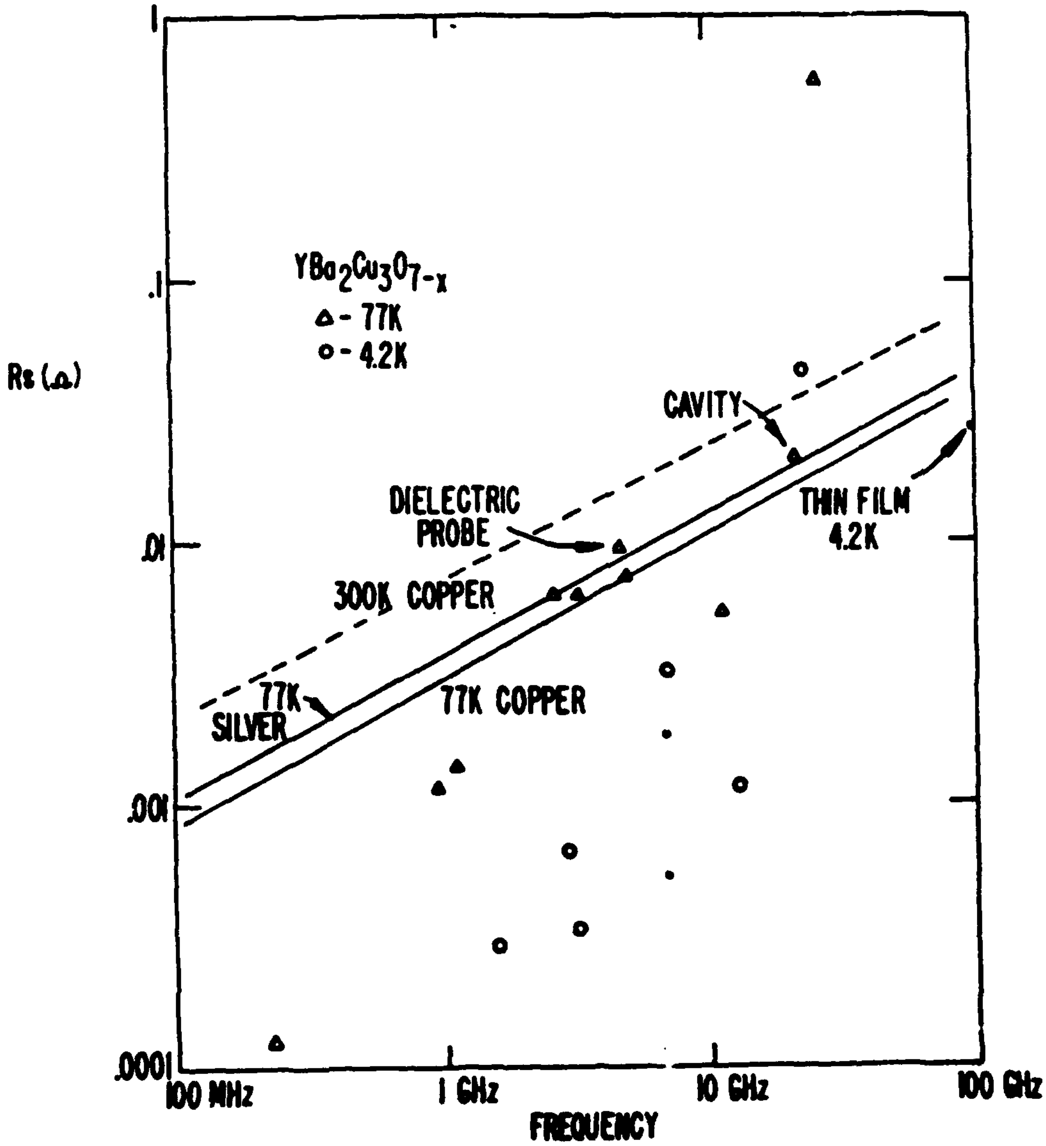

1
.1
.01
.001
.0001
Rs (Ω)
$YBa_2Cu_3O_{7-x}$
Δ - 77K
o - 4.2K
CAVITY
DIELECTRIC PROBE
300K COPPER
THIN FILM 4.2K
77K SILVER
77K COPPER
100 MHz
1 GHz
10 GHz
100 GHz
FREQUENCY

FIG._5.

DIELECTRIC MICROWAVE RESONATOR PROBE

BACKGROUND OF THE INVENTION

The present invention relates to a microwave probe and particularly to a dielectric resonator probe for measuring surface resistance of a test material.

Design and construction of microwave devices requires knowledge of the microwave properties of materials used to construct the device. In the past, a dielectric post resonator has been used to measure room temperature permittivity and permeability of microwave insulators, as described in Marian W. Pospieszalski "On the Theory and Application of Dielectric Post Resonator" *IEEE Transactions on Microwave Theory and Techniques,* Pages 228-231, March, 1977, incorporated herein by reference. A dielectric rod resonator has also been used to obtain the value of the loss tangent of a material as described in Y. Kobayashi, et al, "Microwave Measurement of Dielectric Properties of Low-Loss Materials by the Dielectric Rod Resonator Method", *IEEE Transactions on Microwave Theory and Techniques.* Vol. MTT-33, No. 7, Pages 586-592, July, 1985.

One of the material characteristics of interest is surface resistance. Previous devices for measuring surface resistance have included resonant cavity devices at millimeter wavelengths as described in F. J. Tischer, et al, "Resonant Cavities for the Measurement of the Surface Resistance of Conductors at Millimeter Wavelengths", *Review of Scientific Instruments,* Vol. 46, No. 1, Pages 11-14, January, 1975, incorporated herein by reference.

Previous microwave devices, although usable to provide certain measurements, have been relatively insensitive to small differences in surface resistance. Previous devices have also been difficult to use because of lack of satisfactory mode separation. Furthermore, many previous devices have required a relatively large sample size to make measurements at lower microwave frequencies where measurement accuracy is greatest.

Of particular interest are methods for determining surface resistance of high critical temperature (T_c) superconducting materials. The previous uses of the dielectric post resonator have concentrated on room temperature measurements. Previous devices have not been easily adaptable to operation in cryogenic temperatures such as about 98° K. or less. Measurement apparatus which has been used at low temperatures includes a discresonator apparatus. Such a disc resonator requires special processing of the sample to be tested, such as patterning of the disc. In most cases, the sample preparation destroys the usefulness of the sample for subsequent applications.

SUMMARY OF THE INVENTION

According to the present invention, a modified dielectric post resonator probe is used for obtaining surface resistance of a test material. In the modified probe, the dielectric resonator is positioned between a conductive plate and the test material. The dielectric resonator is spaced from the conductive plate, preferably by a dielectric spacer and is substantially in contact with the test material. In the preferred embodiment, the resonator has a hole extending therethrough which assists in providing higher mode separation. The resonator preferably has a stepped shape to maximize measurement sensitivity by substantially confining losses to the sample being tested. The resonator is mounted using a spring-loaded mounting apparatus to accommodate differential thermal expansion for operation at cryogenic temperatures. Preferably, a conductive shield substantially surrounds the sidewall of the resonator and coupling cables used to electromagnetically excite the resonator extend through the sidewall or through the conductive plate.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an explode perspective view, partially cut away, of the apparatus of the present invention and a test material;

FIG. 2 is a cross-sectional view of the apparatus of the present invention taken along line 2—2 of FIG. 1;

FIG. 3 is a cross-sectional view similar to the view of FIG. 2, but showing a second embodiment of the present invention;

FIG. 4 is a schematic view of the peeled lines of TE_{011}; and

FIG. 5 depicts microwave surface resistance of high T_c superconductors obtained according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

As shown on FIG. 1, the resonator probe apparatus 10 of the present invention includes an upper plate 12, a dielectric resonator 14, and coupling cables 16*a*, 16*b*. The upper plate 12 is made of a conductive material such as copper. The upper plate 12 has a central hole 18 for use in mounting as described below. The upper plate 12 is preferably integrally formed with a cylindrical sidewall 20.

When the probe is assembled as depicted in FIG. 2, the sidewall 20 substantially surrounds the resonator 14. The sidewall 20 is also formed of a conductive material such as copper. In the embodiment depicted in FIG. 1, holes 22*a*, 22*b* are formed in the sidewall to permit insertion of the cables 16*a*, 16*b* through the sidewalls 20 in order to position the ends 24*a*, 24*b* of the cables adjacent the dielectric resonator 14 as depicted in FIG. 2. In the embodiment depicted in FIG. 2, the cables 16*a*, 16*b* are configured for magnetic transmission excitation of the resonator 14. Magnetic loops are formed on the ends of the cables 24*a*, 24*b* and a microwave signal such as a signal having a frequency of about 7 Gigahertz (GHz) is transmitted through the cables 16*a*, 16*b* to cause magnetic excitation of the resonator 14. The apparatus depicted in FIG. 2 is also capable of reflection excitation in which case a signal is provided on only one of the two cables. If reflection excitation is desired, an apparatus can be provided with only a single cable.

The apparatus depicted in FIG. 3 is similar to the apparatus of FIG. 2, except that the cables 16*a*, 16*b* are configured for electrical transmission excitation. In a configuration depicted in FIG. 3 the cable 16*a*, 16*b* pass ends of the cables 28*a*, 28*b* form wave guides for conveying microwave signals for exciting the resonator 14. As with magnetic excitation, the apparatus of FIG. 3 could be used to provide reflection excitation as well as transmission excitation by providing a signal only over one of the two cables 16*a*, 16*b* or by providing only a single cable.

The resonator 14 is made of a dielectric material, preferably having a high permittivity, such as a permittivity of at least about 10, preferably at least about 25. In the preferred embodiment, the dielectric resonator 14 is formed of barium magnesium tantalum oxide (BMT) ceramics. Other materials which can be used to form a dielectric resonator include alumina, Zr/Sn titanate, and barium tetratitanate.

The resonator 14 is formed with an upper surface 32 and a lower surface 34. Preferably, the surface area of the upper surface 32 is less than the surface area of the lower surface 34. The actual surface areas of the upper and lower surface depend upon the material used for the resonator and the frequencies at which testing is to be done since the frequency of a resonator is a function of the permitivity of the material used and the size of the resonator. The surface area of the lower surface 34, which will contact the test material, is less than or equal to the surface area of the test material since the lower surface of the resonator 34 should entirely contact the test material. In the embodiment depicted in FIG. 1, the resonator 14 has a shape which defines segments of two coaxial cylinders, the lower cylinder 36 having a diameter 38 greater than the diameter 56 of the upper cylinder 44. Providing a resonator with a larger surface area in the lower surface 34 than the upper surface 32 increases sensitivity of the apparatus. When measuring resistance, sensitivity is believed related to the areas where loss occurs. In the present apparatus, the amount of loss is related to the surface area of the resonator where it is near the conductive plate 12 and sample 46 respectively. By making the lower surface of the resonator 34, which contacts the sample 46, larger than the upper surface 32 which is positioned near the upper plate 12, a larger portion of the losses occur at the lower surface of the resonator 34, i.e., adjacent the test sample 46. It is believed that in the described apparatus, 80% to 90% of the field is concentrated near the sample 46. By providing most of the loss near the sample, higher sensitivity is obtained.

The resonator 14 preferably includes a hole 48 extending therethrough and forming an opening 52 in the upper surface 32 of the resonator 14. The hole 48 is preferably stepped or countersunk 36 so as to have a larger diameter 54 in the lower portion and a smaller diameter 42 in the upper portion 44. The stepped shape of the hole serves to accommodate a mounting bolt 58 as described more fully below.

The hole 48 increases the mode separation of the device. As described more fully below, an ideal device would operate entirely in a single mode, namely the TE_{011} mode. The field configuration of a TE_{011} is depicted schematically in FIG. 4, in which solid arrows depict the electric field lines 62 and dotted arrows depicted the magnetic field lines 64. In practice, however, several other resonances are present. During measurement, the apparatus is operated to sweep across a plurality of frequencies. Occurrence of the desired TE_{011} frequency is identified by the resonant peak or maximum in the spectrum of the transmitted power or the null in the spectrum of the reflected power. When undesired resonances occur at frequencies which are close to the TE_{011} resonance frequencies, the undesired modes can interfere with the desired mode. The hole 48 tends to increase the frequency separation between the desired mode TE_{011} and undesired modes. Thus, providing the hole 48 makes it easier to use the apparatus so as to identify the desired TE_{011} resonance frequency.

To further increase sensitivity of the instrument, the resonator 14 is mounted so as to be spaced from the upper plate 12. In the embodiment depicted in FIG. 1, spacing is achieved by providing a dielectric spacer 66 positioned between the resonator 14 and the upper plate 12. The dielectric spacer 66 preferably is in the form of a cylinder and has a hole 68 extending therethrough for accommodating the bolt 58. The dielectric spacer 66 preferably has a low dielectric constant of less than about 5. The dielectric spacer can be formed of a number of materials including fluorinated ethylene-propylene resins and tetrafluoroethylene fluorocarbon polymers such as those sold under the trade name TEFLON TM, available from E.I. DuPont de Nemours & Co., Wilmington, Del., and crosslinked polystyrene, such as that sold under the trade name REXOLITE TM, available from American Enka Corp. The dielectric spacer 20 preferably is formed of a low-loss material and preferably has a loss tangent less than about 10^{-4} at room temperature. By forming the device so that the resonator 14 contacts the test sample 46 but is spaced from the conductive upper plate 12, most of the loss which occurs in the device occurs in the region of the specimen 46. Thus, by spacing the resonator 14 from the top plate 12, the losses are concentrated in the sample 46 and the sensitivity of the apparatus is thereby increased.

The apparatus described is particularly useful for measuring surface resistance of the test sample 46 under cryogenic conditions, such as temperatures less than about 90° K. The described device includes a number of components which are made of materials having thermal expansion coefficients which are quite different from one another. According to the present invention, certain components of the device are mounted in a resilient fashion so as to accommodate the differential thermal expansion and absorb the stresses which would otherwise be caused by such differential thermal expansion. In the embodiment depicted in FIG. 1, the resilient mounting apparatus includes a bolt 58 passing through various holes 48, 68, 18, a helical spring 72 and a nut 74. As best seen in FIG. 2, the bolt 58 extends through the holes 48, 68, 18 in the resonator 14, dielectric spacer 66 and upper plate 12. The end of the bolt 58 extends above the upper surface of the plate 12 and through the helical spring 72 to engage the nut 74. Tightening the nut 74 causes the spring 72 to be compressed between the nut 74 and the plate 12. Such compression causes the bolt 58 to exert a force on the resonator 14 urging it in a direction towards the plate 12 and thus maintaining the resonator 14 and dielectric spacer 66 in the configuration depicted in FIG. 2. As the device is cooled to cryogenic temperatures, the plate 12, resonator 14, and dielectric spacer 66 will undergo differential thermal expansion. The stresses caused by the differential thermal expansion, however, will be absorbed by the helical spring 72 and the apparatus can thus be cooled to cryogenic temperatures without stresses from differential thermal expansion accumulating to the point of inducing failure in one of the components. In order that the presence of the bolt 58 should not interfere with the mode separation achieved by the hole 48, the bolt 58 is preferably formed of a non-conducting material such as a thermoplastic resin or REXOLITE TM.

The test sample 46 is preferably mounted in a recess 76 which is formed in a mounting plate 78. In one preferred embodiment, the mounting plate 78 is formed of a material of known conductivity such as copper so that the apparatus 10 can be easily calibrated by positioning the resonator 14 over the plate 78. By forming the resonator 14 with a substantially flat lower surface 34, the resonator **14** can be positioned adjacent the test material **46** as depicted in FIG. **2**.

In operation, the apparatus depicted in FIG. **2** is assembled and cooled to a cryogenic temperature. In one embodiment, the apparatus is positioned in a Dewar jar having a cooling stage cooled by liquid nitrogen. To determine microwave surface resistance of the test material **46**, the quality factor (Q factor) of the structure must be measured. The Q factor is obtained from the relationship:

$$1/Q_{total} = 1/Qd + 1/Q_{top1} + 1/Q_{top2} + 1/Q_{bottom1} + 1/Q_{bottom2} + 1/Q_r$$

where:

$Qd = 1/\tan\delta$ — the dielectric quality factor;

Q_r = the radiation quality factor, which in this case can be omitted since the fields are largely confined in the high permitivity dielectric resonator;

$$\frac{Q_{top1}}{Q_{bottom1}} = \text{the quality factor corresponding to losses in conductive plates directly under the high dielectric, top/bottom respectively;}$$

$$\frac{Q_{top2}}{Q_{bottom2}} = \text{the quality factor corresponding to losses in conductive plates outside the dielectric top/bottom respectively.}$$

Using the measured Q factor, surface resistance is obtained according to the following relationship:

$$Rsmeas = (A/Q_{total} - \tan\delta)/B - R_{sfixt}$$

where;

$$A = 1 + W/\epsilon$$

$$B = (\lambda_o/2L)^3 \cdot (1 + W)/(60\pi^2\epsilon)$$

$$W = \frac{J1^2(\xi)[K0(\zeta) - K1^2(\zeta)]}{K1^2(\zeta)[J1^2(\xi) - J0(\xi)J2(\xi)]}$$

Rsmeas = surface resistance of the sample;

R_{sfixt} = surface resistance of the fixture;

L = length of the dielectric resonator;

ϵ = dielectric constant;

λ_o = wavelength;

$\xi^2 = (2\pi/\lambda_o)^2 - (\pi/L)^2$

$\zeta^2 = (\pi/L)^2 - (2\pi/\lambda_o)^2$

J0, J1, J2, K0, K1, K2 are regular and modified Bessel functions

Further information describing these relationships is found in Kobayoshi, supra.

EXPERIMENTAL

A dielectric resonator probe was used to determine microwave surface resistance of bulk high T_c superconductors such as YBaCuO and BiSrCaCuO. The results are depicted in FIG. 5.

In view of the above description, a number of advantages to the present invention are apparent. The device is operable at cryogenic temperatures and provides increased sensitivity. The device also provides for superior mode separation. Radiation losses are minimized by providing the side shield. The apparatus can be used for non-destructive testing and no special processing or patterning of the sample is needed. Due at least partly to the high dielectric constant of the dielectric resonator materials which can be used in this invention, the surface area of the samples needed for measurement is quite small. For example, a sample with a surface area less than 0.2 cm^2 can be measured at a frequency of 10 GHz while still obtaining desired accuracy of measurement.

Variations and modifications of the described invention can also be used. The apparatus can be provided without mounting the sample **46** in a plate **78**. The resonator **14** can be resiliently mounted using other than the screw and spring mechanism depicted. The apparatus can be operated in non-cryogenic environments. In addition to using the apparatus for obtaining a bulk surface resistance value, the apparatus can be used to probe larger samples of materials, e.g. to locate areas with the best microwave properties.

Although the present invention has been described by way of a preferred embodiment in various modifications, other modifications and variations will also be apparent to those skilled in the art, the invention being defined by the appended claims.

What is claimed is:

1. A dielectric resonator probe apparatus for measuring surface resistance of a test material comprising:
   - a first electrically conductive plate;
   - a spacer comprised of a solid dielectric material;
   - a dielectric resonator having an upper surface, a lower surface and a sidewall, mounted in a substantially fixed position with respect to said plate with said upper surface spaced from said plate by said spacer to maintain said resonator in said substantially fixed position; and
   - means for electromagnetically exciting said resonator.

2. Apparatus as claimed in claim **1**, further comprising:
   - means for positioning said resonator adjacent the test material.

3. Apparatus, as claimed in claim **1**, wherein said dielectric material has a dielectric constant of at least about less than about 5.

4. Apparatus, as claimed in claim **1**, wherein said dielectric material includes material selected from the group consisting of tetrafluoroethylene fluorocarbon polymers, fluorinated ethylene-propylene resins and crosslinked polystyrene.

5. Apparatus, as claimed in claim **1**, wherein said resonator has a permittivity of at least about 10.

6. Apparatus, as claimed in claim **1**, wherein said means for electromagnetically exciting said resonator comprises at least a first cable having an end positioned adjacent said resonator.

7. Apparatus, as claimed in claim **1**, further comprising an electrically conductive shield substantially surrounding said resonator sidewall.

8. Apparatus, as claimed in claim **7**, wherein said means for electromagnetically exciting said resonator comprises at least a first cable extending through said shield.

9. A dielectric resonator probe apparatus for measuring surface resistance of a test material comprising:
   - a first electrically conductive plate;
   - a dielectric resonator having an upper surface, a lower surface and a sidewall, mounted in a substantially fixed position with respect to said plate with said upper surface spaced from said plate to maintain said resonator in said substantially fixed position;

means for relieving stress induced by differential thermal expansion; and

means for electromagnetically exciting said resonator.

10. Apparatus, as claimed in claim 9, wherein said differential thermal expansion occurs upon cooling said apparatus to a cryogenic temperature.

11. Apparatus, as claimed in claim 9, further comprising a spacer comprised of a solid dielectric material, positioned between said resonator and said plate.

12. A dielectric microwave resonator probe apparatus for measuring surface resistance of a test material comprising:

a first electrically conductive plate;

a dielectric resonator having an upper surface, a lower surface, and a sidewall, mounted in a position with respect to said plate with said upper surface spaced from said plate;

means for electromagnetically exciting said resonator; and

means for relieving stress induced by differential thermal expansion wherein said means for relieving stress includes means for resiliently mounting said resonator with respect to said plate.

13. A dielectric resonator probe apparatus for measuring surface resistance of a test material comprising:

a first electrically conductive plate;

a dielectric resonator having an upper surface, a lower surface and a sidewall, mounted in a substantially fixed position with respect to said plate to maintain said resonator in said substantially fixed position;

means for electromagnetically exciting said resonator;

means for positioning said resonator in contact with the test material; and

an electrically conductive shield substantially surrounding said resonator sidewall.

14. Apparatus, as claimed in claim 13, wherein said means for electromagnetically exciting said resonator comprises at least a first cable extending through said shield.

15. Apparatus, as claimed in claim 13, wherein said resonator has a permittivity of at least about 10.

16. Apparatus, as claimed in claim 13, wherein said means for electromagnetically exciting said resonator comprises at least a first cable having an end positioned adjacent said resonator.

17. A dielectric resonator probe apparatus for measuring surface resistance of a test material comprising:

a first electrically conductive plate; and

a dielectric resonator having an upper surface, a lower surface and a sidewall, mounted in a substantially fixed position with respect to said plate, to maintain said resonator in said substantially fixed position said upper surface having a first area, said lower surface having a second area greater than said first area.

18. Apparatus, as claimed in claim 17, wherein said sidewall defines at least a first cylindrical section adjacent said upper surface, having a first diameter and a second cylindrical section adjacent said lower surface, having a second diameter greater than said first diameter.

19. A dielectric resonator probe apparatus for measuring surface resistance of a test material comprising:

a first electrically conductive plate;

a dielectric resonator having an upper surface, a lower surface and a sidewall, and having a resonator hole extending from said lower surface to said upper surface;

a spacer, having a spacer hole substantially aligned with said resonator hole, said spacer positioned between said upper surface of said resonator and said plate;

means for mounting said dielectric resonator in a substantially fixed position with respect to said plate to maintain said resonator in said substantially fixed position.

20. Apparatus as claimed in claim 19, wherein said means for mounting includes a substantially non-conducting mounting device which extends through said resonator hole.

21. A dielectric resonator probe apparatus for measuring surface resistance of a test material comprising:

a first electrically conductive top plate;

a dielectric resonator having an upper surface, a lower surface and a sidewall; and

means for resiliently attaching said dielectric resonator to said top plate in a substantially fixed position spaced a first distance from said plate to maintain said resonator at said first distance from said plate.

22. A dielectric resonator probe apparatus for measuring surface resistance of a test material:

a first electrically conductive plate;

a dielectric resonator having an upper surface, a lower surface and a sidewall;

means for resiliently mounting said dielectric resonator in a position spaced from said plate wherein said means for resiliently mounting includes:

a non-conducting bolt extending through said resonator and said plate and engaging a nut; and

a spring urging said nut in a direction away from said plate.

23. A dielectric resonator probe apparatus for measuring surface resistance of a test material comprising:

a first electrically conductive plate;

a dielectric spacer positioned adjacent said plate;

a dielectric resonator resiliently mounted with respect to said plate and spaced from said plate by said dielectric spacer, said resonator having an upper surface, a lower surface, and a sidewall, said sidewall defining at least a first cylindrical section adjacent said upper surface having a first diameter and a second cylindrical section adjacent said lower surface having a second diameter greater than said first diameter, said dielectric resonator having a hole extending from said lower surface to said upper surface;

an electrically conductive shield substantially surrounding said resonator sidewall and integrally formed with said first electrically conductive plate;

at least a first cable extending through one of said plate and said shield and having an end position adjacent to said resonator; and

means for mounting said resonator in a substantially fixed position with respect to said plate, to maintain said resonator in said substantially fixed position said means including a non-conductive mounting device extending through said hole.

24. A method for measuring surface resistance of a test material, comprising:

providing a dielectric resonator probe which includes:

a first electrically conductive plate;

a dielectric resonator having an upper surface, a lower surface and a sidewall;

means for mounting said dielectric resonator in a position spaced from said plate;

means for electromagnetically exciting said resonator;

cooling said probe and said test material to a temperature below about 90° K.;

positioning said test material adjacent said lower surface;

exciting said resonator using said means for electromagnetically exciting;

measuring the Q factor of said test material; and

determining surface resistance of said test material, using the Q value measured in said step of measuring.

25. A method, as claimed in claim **24**, further comprising:

calibrating said probe by positioning said lower surface adjacent a second conductive plate.

26. A method, as claimed in claim **24**, wherein said step of providing a dielectric resonator probe includes providing a probe which has a dielectric material position between said resonator and said plate.

27. A method, as claimed in claim **24**, wherein said step of providing a dielectric resonator probe includes providing a dielectric resonator having said upper surface with a first area less than the area of said lower surface.

28. A method, as claimed in claim **24**, wherein said step of providing a dielectric resonator probe includes providing a means for mounting said dielectric resonator and for simultaneously relieving stress induced by differential thermal expansion.

* * * * *

APPENDIX D

NOVEL FILTER IMPLEMENTATIONS USING HTS MATERIALS

Novel filter implementations using HTS materials

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ABSTRACT

New high temperature superconductor(HTS) materials offer several advantages at microwave frequencies especially in satellite payload applications,including improvement of insertion loss of typical microwave components such as filters and multiplexers.

However, the price we have to pay for such improvement involves increasingly complicated thermal design of the satellite to provide required cooling. To justify the use of superconductors not only improvement of loss must be taken into consideration, but also the possibility of new, specific to HTS, microwave designs, which could offer reduction in size and weight.

In this paper such novel implementations of the filters will be presented. A hybrid approach utilizing HTS and very loss dielectric resonators will be shown. Narrow band microstrip filter configurations (including elliptic designs required to meet satellite transponder requirements) will also be discussed. Trade-off analysis will be performed and recommendations for the best design will be given.

1. INTRODUCTION TO HTS FILTERS

Interest in HTS material applications has exploded in the past few years with the introduction of truly usable HTS fabrication techniques. A natural target for this attention is in the microwave components field, where resistive losses are most severe. Current HTS materials (thin films in particular) offer the possibility of over two orders of magnitude improvement in resistive losses. These losses are usually small in conventional microwave circuitry, but are crippling in narrowband filter applications. As a result, very large and bulky waveguide filters are often substituted for the lighter wideband designs. These waveguide narrowband designs are used as channelizing(input) and combining(output) filters for communications satellite payloads. Figure 1 depicts the block diagram of a typical satellite transponder.

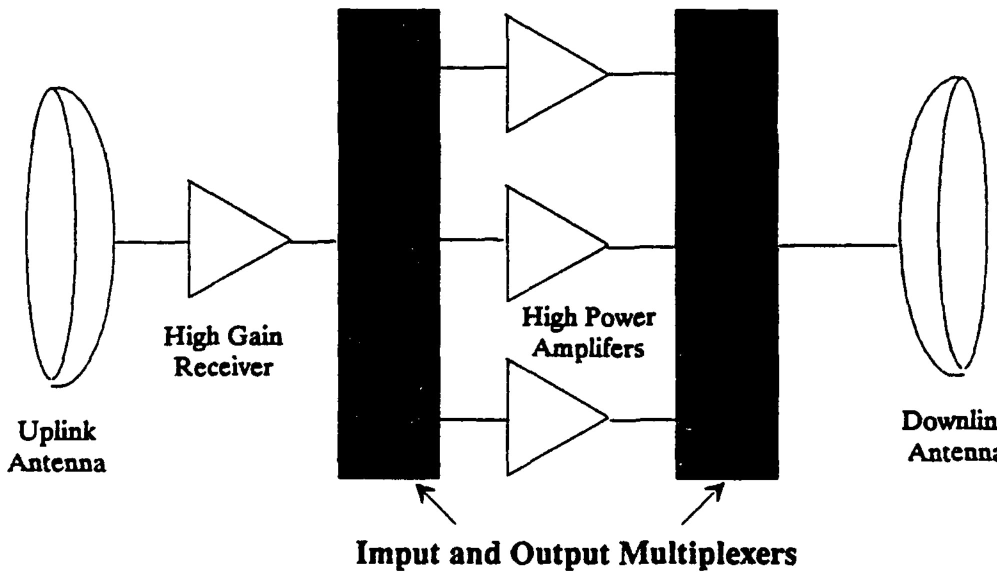


Figure 1 Simplified Satellite Transponder Block Diagram

Filters and multiplexers comprise a substantial portion of the payload and are a major contributor to the weight, size, cost, and power dissipation of the satellite. This diagram is a simplified one, just to show function. In a typical transponder, there are usually at least 50 narrowband filters, each using a bulky waveguide design (Figure 2). With the size reductions possible in other(active) components, these filters are a true stumbling block to radical miniaturization of the satellite transponder. If HTS materials could be used in these applications in a reasonable way, considerable savings in size, mass, power dissipation, and cost might be achieved. In the following sections, several different methods of using HTS in filters are discussed.

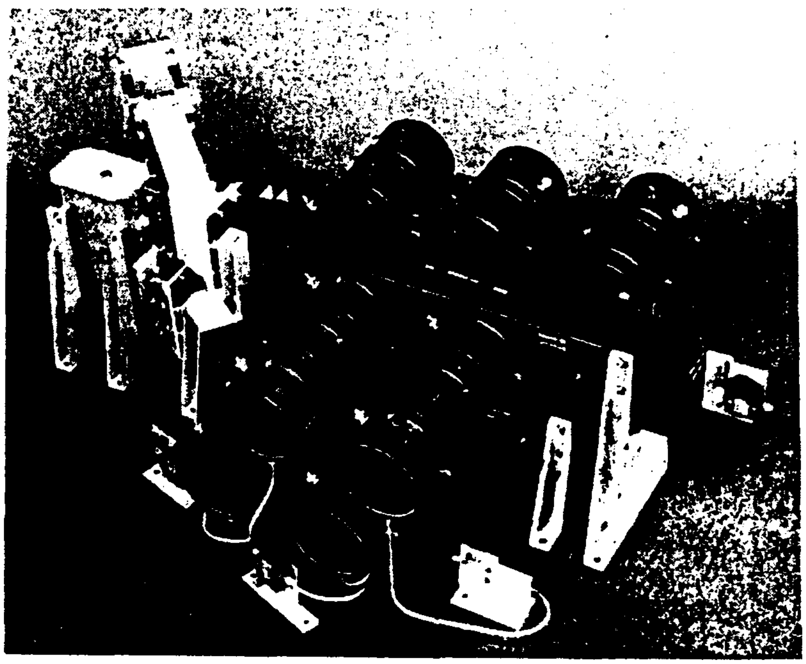


Figure 2 Waveguide Output Multiplexer(4 GHz)

2. POTENTIAL DESIGN TECHNIQUES

2.1 Microstrip

The typical design for a filter compatible with active circuitry is the microstrip filter. Relatively easy to design and fabricate, it is a convenient filter for use with wideband applications. However, it depends almost completely on the conductivity of the microstrip lines and is thus extremely lossy due the relatively small dimensions of the linewidths. A typical satellite transponder input filter would use an eight pole filter to achieve the kind of steep rejection skirts and flat passband required for high rate digital communications. Implemented in waveguide, the center band loss is about .5 dB, in microstrip it would be 8 dB! Figure 3 illustrates the difference in passband performance between waveguide and microstrip, as well as the same microstrip filter using the recent HTS thin films.

The use of HTS brings the microstrip filter close to that of the waveguide filter, but at a fraction of the size and weight(and probably cost). This sounds attractive, but a number of difficulties remain.

Typical transponders vary in channel bandwidth from 18 to 120 MHz, with filtering tuned to within less than 1 MHz of the ideal center frequency and bandwidth.In addition, very careful tuning is also required to achieve desirable passband characteristics, such as flat group delay. Designing a microstrip filter, even with ultra high HTS derived Q factor, to such close tolerances without an inordinate number of iterations presents a severe challenge for current design tools. The necessity for cryogenic temperatures creates further problems, since the filters are basically inoperative at room temperatures and probably untunable(with tuning pads) at cooled temperatures(due to physical constraints). Also, the poor temperature stability of the microstrip designs means each design will operate satisfactorily only in a narrow temperature range.

For state-of-the-art satellite transponders, the typical Chebychev and Butterworth filter designs do not have sufficiently high performance. Elliptic and quasi-elliptic designs are more common, due to their more optimum skirt steepness for a

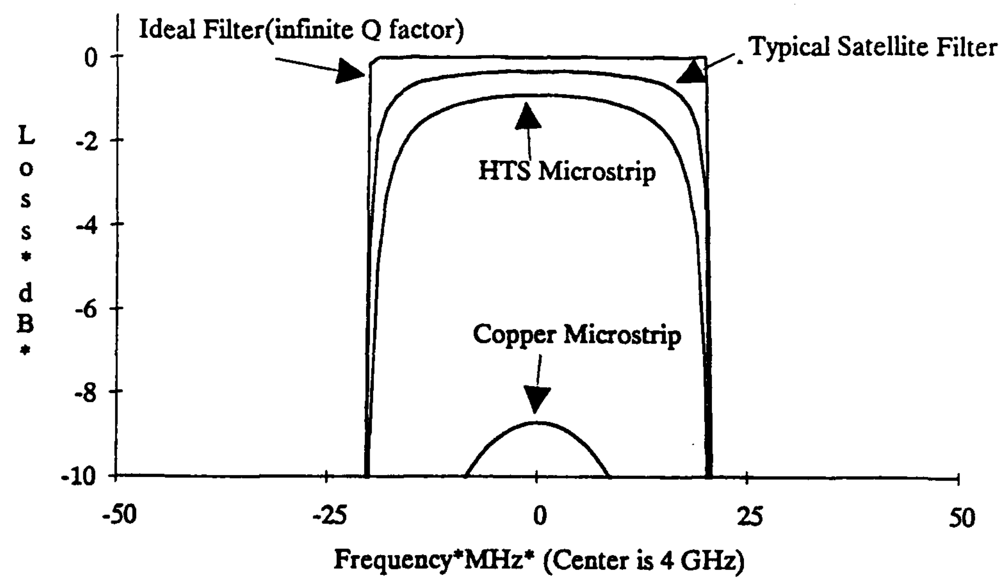


Figure 3 Losses of Microwave Filters

given number of poles. Figure 4 shows the comparison between an 8 pole elliptic filter and an 8 pole Chebychev filter

meeting the same out of band rejection specifications. The Chebychev is inadequate even with infinite Q factor. Elliptic and quasi-elliptic designs require couplings between non-adjacent resonances, which is usually incompatible with conventional edge coupled microstrip designs. A new, novel Ford Aerospace design(patent pending) proposes to neatly solve this dilemma by substituting dual, orthogonal mode resonators for the long strip resonators currently used. Figure 5 shows an example layout for a 4 pole filter of this type. This design is analogous in microstrip to dual mode resonators implemented in cylindrical waveguide. Another advantage of this design are the relatively wide linewidths, maximizing the *critical* Q factor of the filter. Diagonal cuts at a corner of the resonator provide coupling between modes, and conventional edge coupling for adjacent resonator squares.

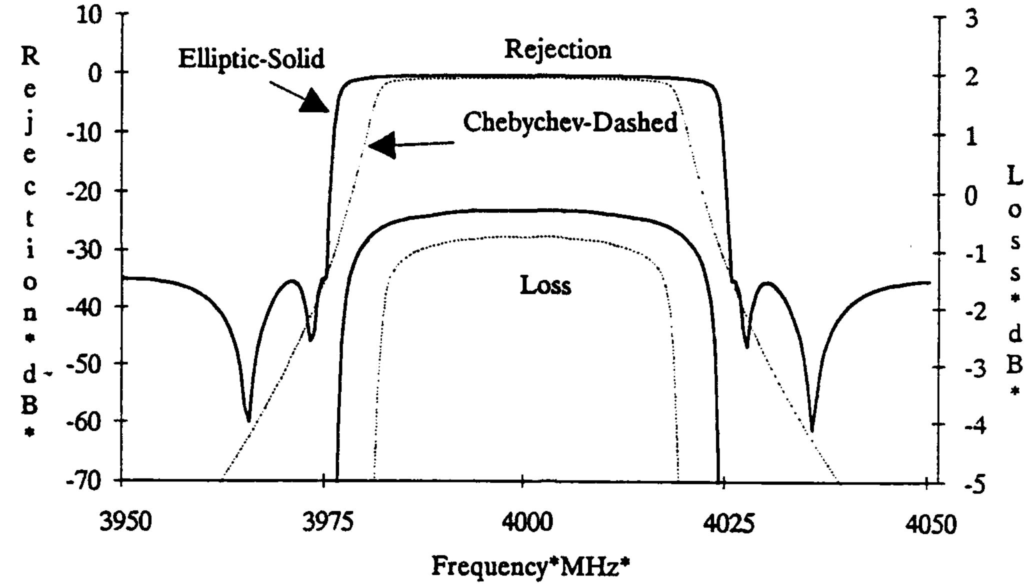


Figure 4 Comparison of Chebychev and Elliptic Filters

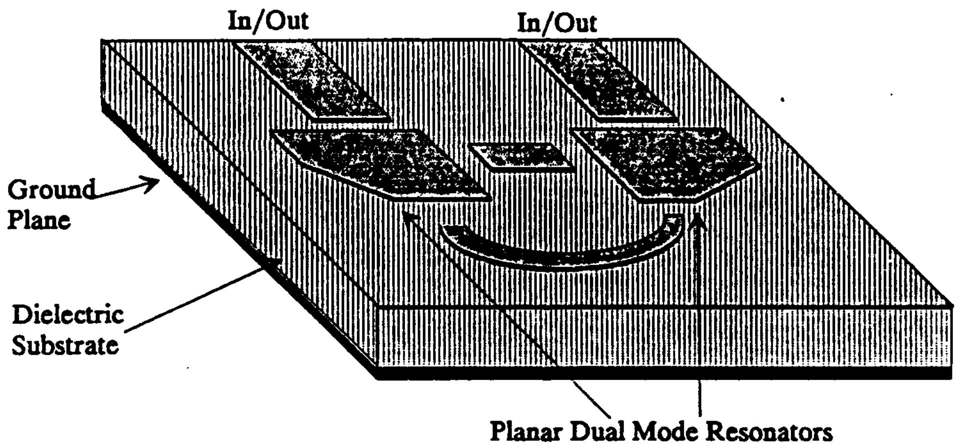


Figure 5 Novel Microstrip Filter Configuration

2.2 Waveguide cavity

An obvious application of HTS materials is to line waveguide cavities with HTS or to construct cavities entirely of HTS. Many companies are pursuing this option, in particular for hydrogen maser cavities. Considerable reduction in size in possible with this technology. Even so, however, the size of filters constructed using this method are still excessively large. In addition, current technology does not allow deposition of HTS thin films (best performance) on any suitable cavity materials. As a result, current cavities are typically made from bulk material, which is typically only somewhat better than copper at best. A possible application of bulk cavities is in output multiplexing, where losses are very costly and small size may not be desirable due to the possibility of arcing or multipactor discharge.

2.3 Hybrid dielectric resonator

A unique approach being developed by Ford Aerospace is the use of dielectric resonators in conjunction with HTS ceramics. We have long used high dielectric constant ceramics to shrink microwave filter size by more than 50%[1]. Figure 6 depicts the size reduction possible using dielectric resonators at 12 GHz in high performance satellite filter applications. Ford Aerospace has built and flown hundreds of these filters.

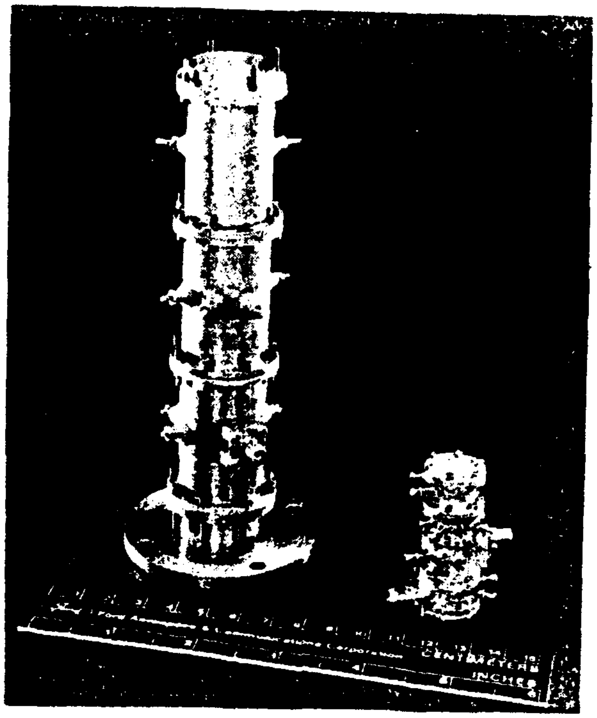


Figure 6 Comparison of Conventional Waveguide and Dielectric Resonator Filters(12 GHz)

Normally, dielectric resonators are usually supported in a waveguide cavity below cutoff as shown in Figure 7. The surrounding cavity is kept significantly larger than the resonator to minimize the Q factor degradation associated with the surrounding metal walls. As a result, the size reduction possible is reduced to the extent that Q factor is increased. This is exacerbated by the necessity of supporting the resonator in the center of the cavity, further reducing the Q factor due to the finite loss tangent of the holder.

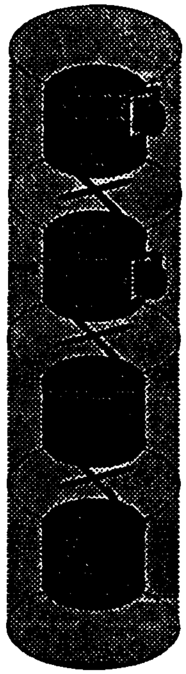


Figure 7 Dielectric Resonator Filter Configuration

A solution to these problems is the use of HTS materials as a substitute for the metal walls of the cavity. However, it is difficult to place thin films of HTS on an entire cavity wall so we have developed a post configuration where only the end walls are HTS material. In addition, since the HTS loss is very small, the resonators can be placed flush against the end walls minimizing the volume of the filter. A further advantage of this method is the extremely high Q factor of dielectric resonators at cryogenic temperatures, as much as 140,000[2]. In fact, this configuration is used by Ford Aerospace for measurement of superconductors[3]. A particular note is that HTS material is only required under the resonator, reducing the necessary size of the substrates.

Advantages of this design are:

1. Exceptional Q factor due to HTS endwalls and low dielectric loss
2. Small size due to high dielectric constant of ceramics
3. Tunability- A critical factor for sophisticated multipole responses
4. Functionality at room temperature-alignment is greatly simplified
5. Excellent temperature stability
6. Any HTS material can be easily substituted.
7. Double sided thin films are not required.

Figure 8 shows the configuration of a 4 pole hybrid dielectric resonator post filter using HTS material, as well as expected performance of the filter. The TE011 mode provides one pole per resonator and has the advantage of its fields being strongest at the endwalls, maximizing the effect of the HTS conductivity. Q factor expected for this filter using a high quality thin film is over 50000 at 77K, where reflection losses will be dominant for virtually any application.

Q factor over 50000 (8 GHz) with HTS Thin Film

Compact-2.5"x.5"x.6"

Lightweight-45g.

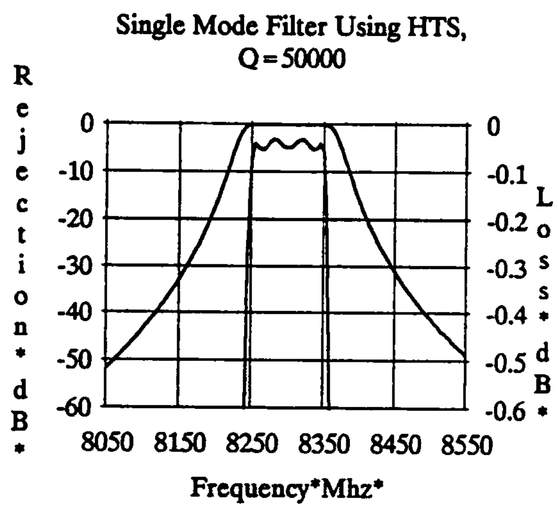
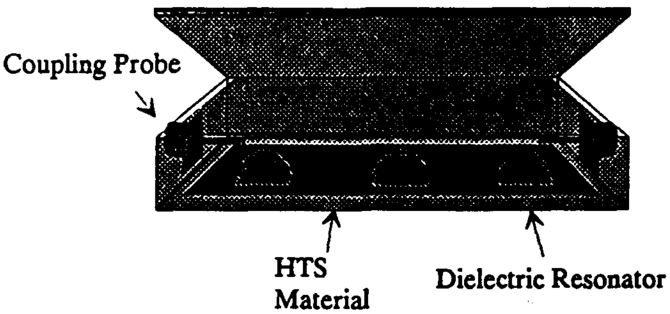


Figure 8 Single Mode Post Dielectric Resonator Configuration and Expected Performance

Several other designs have been developed at Ford Aerospace depending on the application need. Figure 9 shows a half cut dielectric resonator filter and its expected performance. This design has the advantage of requiring only one side with HTS material, reducing size and cost at the expense of lowered Q factor. An further extension of this idea is shown in Figure 10, where the resonator is cut down to quarter size, offering the minimum volume, but with two sides of HTS and reduced Q factor. A further advantage of the quarter cut design is the effective elimination of spurious HE modes. Any of these designs may be easily extended to include non-adjacent resonator couplings through simple mechanical means and are thus suitable for steep satellite channel filters.

Current waveguide and dielectric resonator designs often use dual mode (two poles per physical resonator) cavities to reduce size and weight. Figure 11 shows an HTS/Dielectric resonator hybrid design using the HE111 dielectric resonator mode(two orthogonal modes per cavity). In this case, no HTS is used between the resonators to allow interresonator coupling, although an alternate design might place a superconducting substrate with a coupling slot between the resonators to minimize size.



Q factor over 30000 (8 GHz) with HTS Thin Film
Compact-2.5"x.4"x.6"
Lightweight-40g.

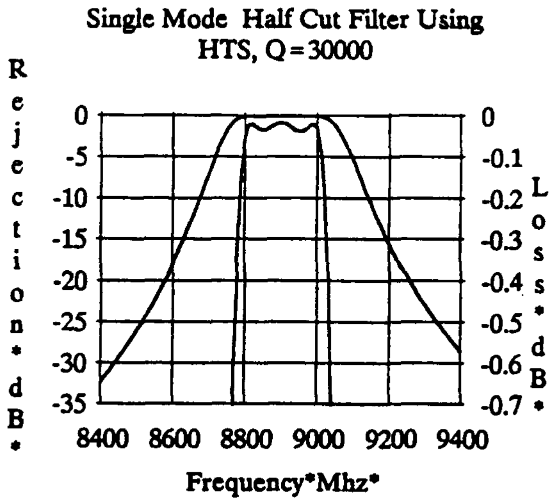
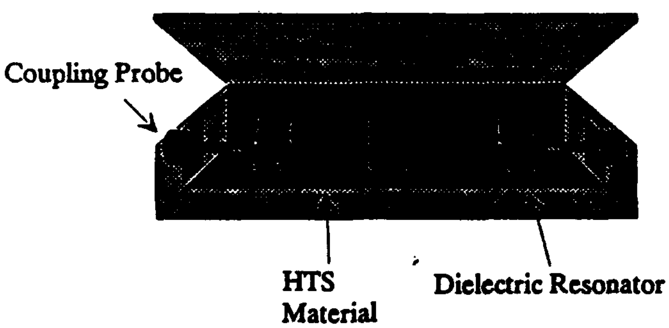


Figure 9 Single Mode Half Cut Dielectric Resonator Configuration and Expected Performance



Q factor over 25000 with HTS Thin Film
Compact-2.5"x.4"x.4"
Lightweight-38g.

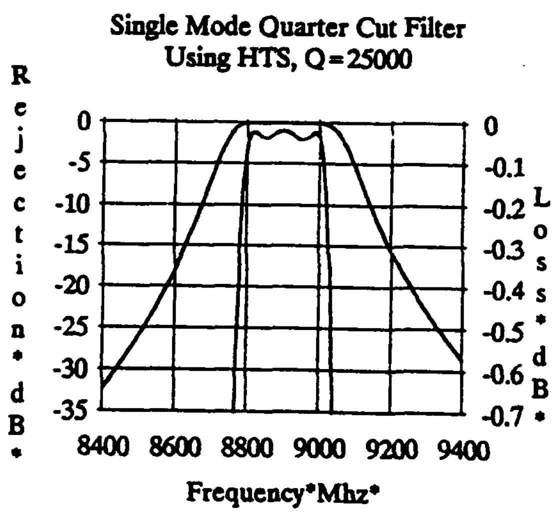


Figure 10 Single Mode Quarter Cut Dielectric Resonator Configuration and Expected Performance

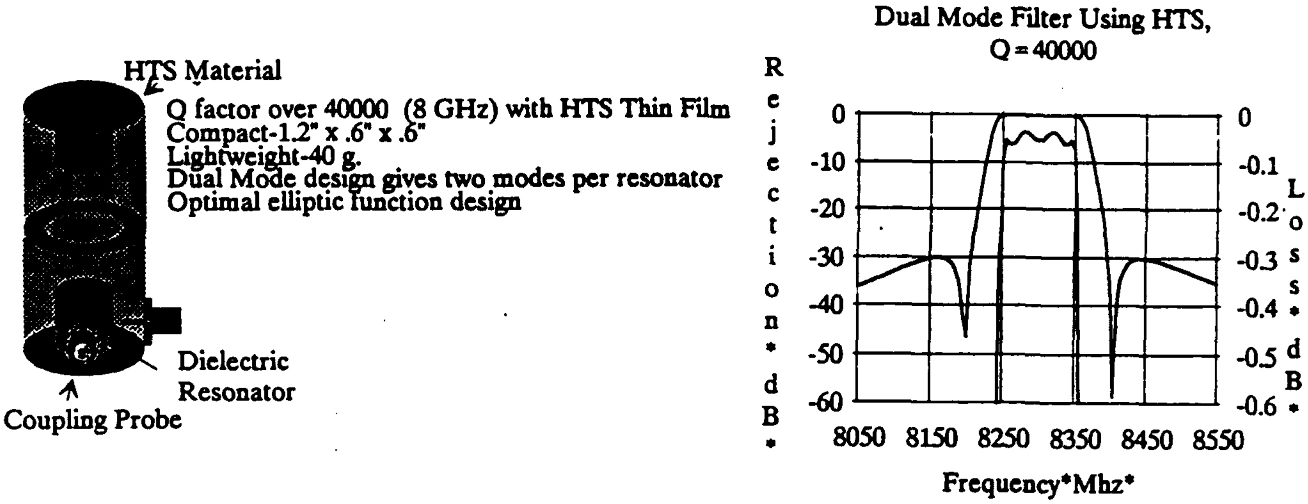


Figure 11 Dual Mode Dielectric Resonator Configuration and Expected Performance

4. CONCLUSION

Various designs for HTS filters have been reviewed and the conclusions summarized in Table I.

Table I Comparison of HTS Filters

Resonator Type	Size	Loss	Cost	Temperature Stability	Tunability
Microstrip	Small	Moderate	Low in quantity High in small lots	Poor	Poor(New Mask required for each iteration)
Cavity	Large	Very Low	High	Fair	Good
Dielectric Resonator	Small	Low	Moderate	Excellent	Excellent

Clearly, further advances in this technology are fundamentally controlled by the development of higher Tc superconductors. In addition, processing technologies, especially for the microstrip designs is of utmost importance.

The HTS/dielecuric resonator filters described here offer a relatively small and low cost alternative which exhibits exceptionally high performance.

5. REFERENCES

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[2] Y. Kobayashi, Y. Kabe, Y. Kogami, and T. Yamagishi, "Frequency and Low-Temperature Characteristics of High-Q Dielectric Resonators," 1989 IEEE MTT-S Symposium Digest, pp. 1239-1242, June 1989

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APPENDIX E

HYBRID DIELECTRIC/HTS RESONATORS AND THEIR APPLICATIONS

HYBRID DIELECTRIC/HTS RESONATORS AND THEIR APPLICATIONS

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ABSTRACT

Interest in HTS material applications has exploded in the past few years fueled by continuing progress in superconductor fabrication techniques. However, in typical microwave structures utilizing these materials in the form of thin films, HTS compatible dielectric substrates and their dielectric losses are a performance limiting factor. This paper presents a novel concept of using dielectric resonators in conjunction with HTS materials. This hybrid approach offers several advantages: dielectric resonator materials have extremely low losses at cryogenic temperatures, reduced size in comparison to traditional dielectric resonators, exceptional temperature stability, tunability, and versatility (any HTS material can be easily substituted in the proposed filter structures).
Basic dielectric /HTS resonator structures are shown. Novel filter configurations utilizing these resonators and experimental results are presented.

INTRODUCTION

Introduction of practical HTS materials has sparked a tremendous amount of research into potential applications for this important new technology. A natural target for this attention is in the microwave components field, where resistive losses are severe. Current HTS materials (thin films in particular) offer the possibility of over two orders of magnitude improvement in resistive losses. These losses are usually small in conventional microwave circuitry, but are crippling in narrowband filter applications, as are used on satellite communications transponders.

Filters and multiplexers are a major contributor to the weight, size, cost, and power dissipation of the satellite. In a typical transponder, there are often at least 50 narrowband filters, each using a bulky waveguide design. With the size reductions possible in other(active) components, these filters are a true stumbling block to radical miniaturization of the satellite transponder. If HTS materials could be used in these applications in a reasonable way, considerable savings in size, mass, power dissipation, and cost might be achieved. In this paper, a novel technique combining the low electrical resistance of HTS materials and the size reductions available using dielectric resonators is presented.

HYBRID DIELECTRIC /HTS RESONATORS

In the past, a number of different filter configurations based on high dielectric constant, low loss ceramics have been developed[1,2,3]. These techniques involved suspending a cylindrical resonator inside a waveguide cavity below cutoff. One of the basic advantages of a dielectric resonator as compared to a dielectric filled cavity is the significant reduction of conductive losses affecting the overall Q factor of the structure. Evanescent fields outside of the dielectric resonator practically vanish of a properly designed metal enclosure of the resonator.

Therefore dielectric losses (loss tangent) dominate and determine the Q factor of the dielectric resonator. However, such a structure is somewhat larger than a same frequency metal wall cavity filled with a similar dielectric. Using traditional metals for partial walls of the dielectric resonator and creating "post" dielectric resonators, quarter, or half cut image resonators results in significant degradation of the Q factor due to conductive losses in partially metal coated dielectric resonators. Typical modes used and their field distributions are shown in Figure 1. These resonators can be easily designed using published formulas[4,5,6]. Using newly developed HTS materials practically eliminates conductive losses and the excellent dielectric properties (Q factor) of the typical structures are retained. This is the basic idea for hybrid dielectric/HTS resonators. Utilization of these resonators further reduces the size and weight of the filter structures, due to reduced size of the enclosures. Such reductions are very important in size and weight constrained satellite applications.

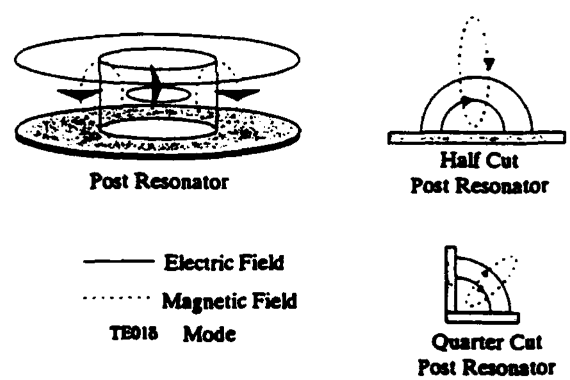

Figure 1 Field Distributions for Various Dielectric Resonator Configurations

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A great deal of research into HTS fabrication has been spent finding suitable substrate materials and developing reliable methods of thin film deposition. Recent developments have produced good films, typically on Lanthanum Aluminate or a related compound. However, these substrate materials seriously degrade device performance due to their relatively high loss tangent. Recently ceramics from a number of companies have shown exceedingly high Q factor at low temperatures. Figure 2 shows the Q factor of a Er=25 ceramic over a range of temperatures. Kobayashi[7] has reported that this type of ceramic can achieve Q factors of over 140,000 at 77K. This characteristic has been used to measure the quality of HTS films[8]. Virtually eliminating dielectric losses leaves only dissipation due to the finite conductivity of the cavity walls. Either the cavity can be enlarged(limited by waveguide moding) or the metal walls replaced with HTS material. HTS walls are particularly attractive since they can be placed directly in contact with the dielectric with little degradation of performance, producing a highly miniature, extremely high Q resonator. In addition, the HTS substrate itself may be of any material.

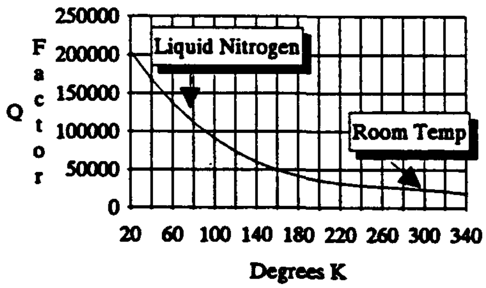

Figure 2 Q Factor of High Dielectric Constant Ceramic

FILTER CONFIGURATIONS

Since HTS thin films have been primarily deposited on flat substrates, the filters presented use HTS on the ends of the resonators only. They are optimized to concentrate the fields most strongly in the HTS regions.

Figure 3 shows the configuration of a 3 pole hybrid dielectric resonator post filter using HTS material. The TE011 mode provides one pole per resonator and has the advantage of its fields being strongest at the endwalls, maximizing the effect of the HTS conductivity. Q factor expected for this filter using a high quality thin film is over 50000 at 77K, where reflection losses will be dominant. Figure 4 shows a half cut dielectric resonator filter. The design has the advantage of requiring only one side with HTS material, reducing size and cost at the expense of lowered Q factor. An further extension of this idea is to cut the resonator down to quarter size, offering the minimum volume, but with two sides of HTS and reduced Q factor. A further advantage of the quarter cut design is the effective elimination of spurious HE modes. This type of design has been used at low frequencies for cellular ground stations [9]. Any of these designs may be easily extended to include non-adjacent resonator couplings through simple mechanical means and are thus suitable for steep satellite channel filters.

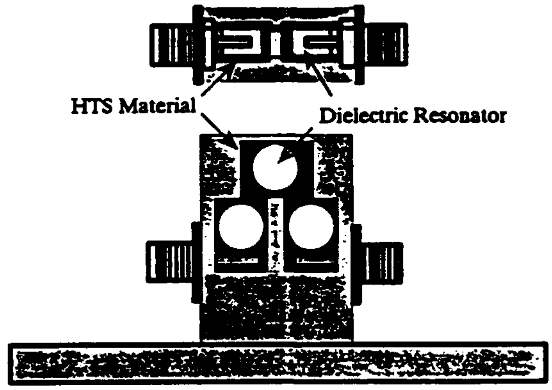

Figure 3 Single Mode Post Dielectric Resonator/HTS Filter

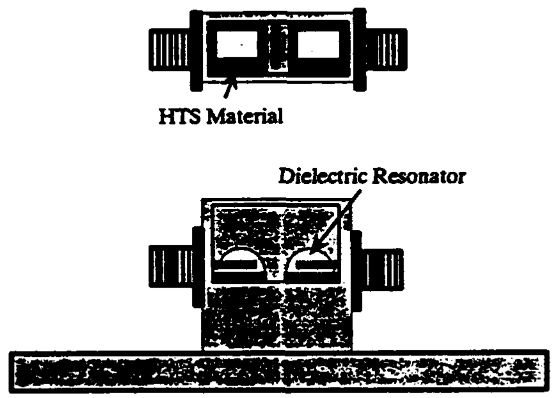

Figure 4 Single Mode Half Cut Dielectric Resonator/HTS Filter

Current waveguide and dielectric resonator designs often use dual mode (two poles per physical resonator) cavities to reduce size and weight. Figure 5 shows an HTS/Dielectric resonator hybrid design using the HE111 dielectric resonator mode(two orthogonal modes per cavity). In this case, no HTS is used between the resonators to allow interresonator coupling, although an alternate design might place a superconducting substrate with a coupling slot between the resonators to minimize size.

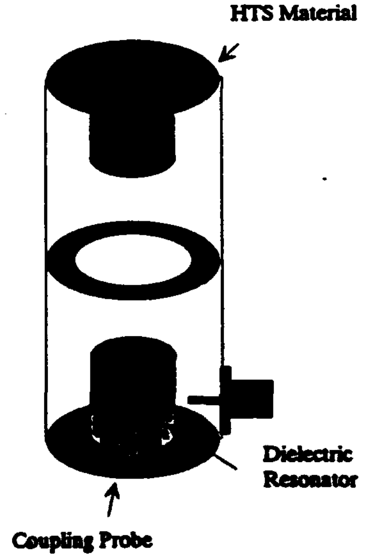

Figure 5 Dual Mode Dielectric Resonator/HTS Filter

EXPERIMENTAL RESULTS

A number of dielectric resonator filters were fabricated for the Naval Research Laboratories' High Temperature Superconductor Space Experiment(HTSSE). A three pole Chebychev design was chosen for a single mode post design. Testing took place by initially using substitute copper substrates to rough tune the filter and to size the resonators. Final tuning involved installing the HTS substrates and tuning the filter while cooled with liquid nitrogen. This technique resulted in an excellent , well tuned filter characteristic. Figure 6 shows the passband performance of the single mode dielectric resonator/HTS filter. Figure 7 depicts the flight single mode filter. Center band loss is .2 dB, with large improvements possible using better HTS films as well as with a somewhat larger cavity enclosure. A two pole half cut resonator design also demonstrated excellent performance, as shown in Figure 8. Figure 9 shows the flight half cut filter.

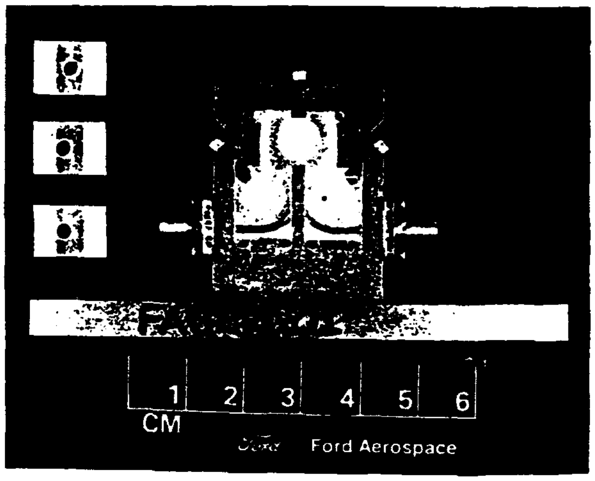

Figure 7 Flight Model Single Mode Post Dielectric Resonator/HTS Filter

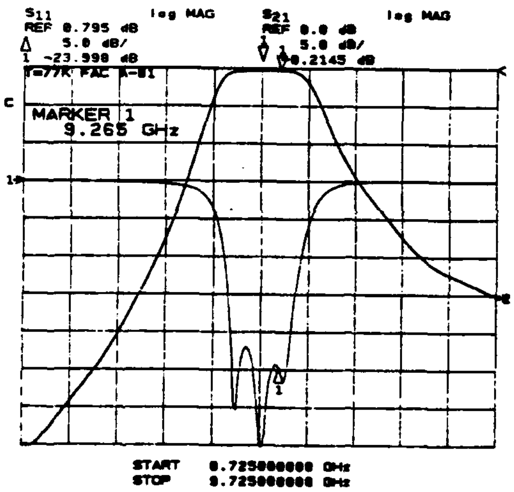

Figure 6 Measured Performance of Single Mode Post Dielectric Resonator/HTS Filter

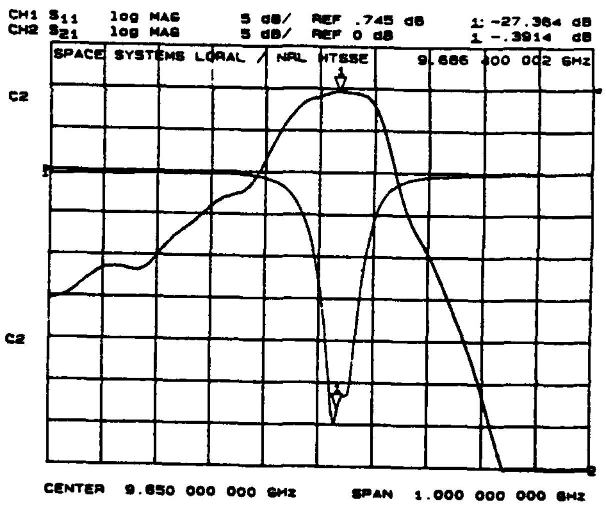

Figure 8 Measured Performance of Half Cut Dielectric Resonator/HTS Filter

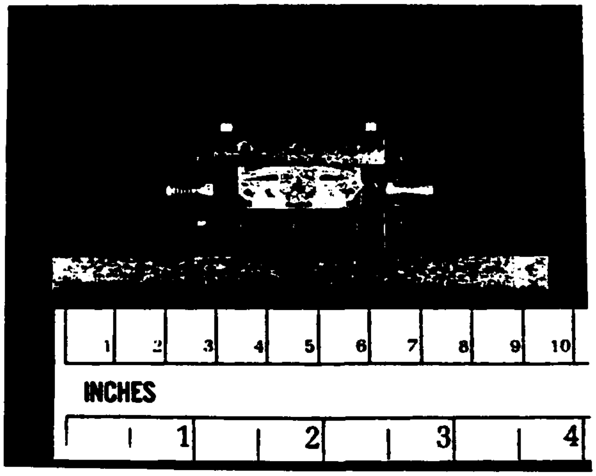

Figure 9 Flight Model Half Cut Dielectric Resonator/HTS Filter

CONCLUSION

A novel technique for realizing extremely high performance, compact filters has been demonstrated. This dielectric resonator/HTS combination offers a variety of advantages for use in narrowband filter applications, where high Q factor and precise alignment are required. Table I shows a comparison of various HTS filter techniques.
Clearly, further advances in this technology are fundamentally controlled by the development of higher Tc superconductors. In addition, processing technologies, especially for the microstrip designs is of utmost importance. The HTS/dielectric resonator filters described here offer a relatively small and low cost alternative which exhibits exceptionally high performance.

ACKNOWLEDGEMENTS

This work was sponsored by the Naval Research Laboratory on contract N00014-89-C-2248, under the direction of Dr. Martin Nisenoff, with the formal collaboration of NASA/Lewis Research Center. The contributions of Dr. Kul Bhasin and Dr. Joseph Warner of NASA/Lewis Research Center in the fabrication of HTS thin films are gratefully acknowledged.

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Table I Comparison of HTS Filter Designs

Resonator Type	Size	Loss	Cost	Temperature Stability	Tunability
Microstrip	Small	Moderate	Low in quantity High in small lots	Poor	Poor
Cavity	Large	Very Low	High	Fair	Good
Dielectric Resonator	Small	Low	Moderate	Excellent	Excellent

APPENDIX F

US PATENT APPLICATION
HYBRID DIELECTRIC RESONATOR/HIGH TEMPERATURE
SUPERCONDUCTOR FILTER.

Attorney Docket No. 14586-28/91-2

PATENT APPLICATION

HYBRID DIELECTRIC RESONATOR/ HIGH TEMPERATURE SUPERCONDUCTOR FILTER

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PATENT
14586-28/91-2

HYBRID DIELECTRIC RESONATOR/ HIGH TEMPERATURE SUPERCONDUCTOR FILTER

SPONSORSHIP

This invention was made under contract with and supported by The United States Naval Research Laboratory, under contract No. N00014-89-C-2248. Rights in this invention have been retained by the contractor.

BACKGROUND OF THE INVENTION

This invention relates to the field of filtering electromagnetic energy in the microwave region in connection with a high temperature superconductor in certain configurations of microwave frequency resonator-filter combinations. Superconductive materials and particularly the recently developed high temperature superconductor (HTS) offer potential advantages when used in connection with microwave components such as filters and multiplexers. Among the primary advantage is a potential for substantial decrease in insertion loss. In specific applications, such as satellite payload applications, the potential for improvement must be weighed against the disadvantage of increasingly-complicated thermal design to provide the required cooling. What is needed is a new type of microwave filter design which can provide significant reductions in size and weight sufficient to justify the added complication of cooling.

The following references have been noted as a potentially relevant to the subject invention:

Carr, "Potential Microwave Applications of High Temperature Superconductors", Microwave Journal, December 1987, pp. 91-94. This paper discusses some of the advantages of using superconductors and microwave structures. One of the advantages is lower loss. Notwithstanding, there is nothing that suggests the structure of the present invention.

Braginski et al. "Prospects for Thin-film Electronic Devices Using High-T_c Superconductors", <u>5th International Workshop on Future Electron Devices</u>, June 2-4, 1988, Miyagi-Zao, pp. 171-179. This paper discusses HTS technologies with representative device high frequency transmission strip lines, resonators and inductors. It also highlights in general terms alternative processes for the film fabrication. It doesn't address the structures themselves and how they might be employed in a specific resonator structure.

Zahopolis et al., "Performance of a Fully Superconductive Microwave Cavity Made of the High T_c Superconductor $Y_1Ba_2Cu_3O_y$", <u>Applied Physics Letters</u>, Vol. 52(25), 20 June 1988, pp. 2168-2170. This paper describes a cavity fabricated with high temperature superconductive materials. The resonator employs a medium dielectric constant resonator which substantially fills a conductive cavity in a experimental structure. There is no way to tune because it is a fully enclosed structure, so it is not functional as a resonator. There are no teachings as to how to use a dielectric resonator within a cavity where the cavity itself is not fully superconductive.

U.S. Patent Nos. 4,453,146, 4,489,293 and 4,692,723 are representative of work done on behalf of the predecessor to the assignee of the present invention. They describe various narrow band dielectric resonator/filters. There is no suggestion whatsoever in these patents of how to make effective use of superconductive materials as a wall or a portion of wall cavity.

Warskey, U.S. Patent No. 4,918,050 issued April 17, 1990. This patent describes a reduced size superconductive resonator including high temperature superconductors. This patent describes a TEM mode resonator in which the cavity is constructed of superconductive material wherein a finger of the superconductive material extends within the wall of the cavity, and in which the cavity itself is filled with a high dielectric constant material. Since this is a TEM or quasi-TEM mode resonator, its structure cannot be readily compared to a TE mode structure.

Cone et al., U.S. Patent No. 4,918,049 issued April 17, 1990. This patent discloses a microwave/far infrared cavity and waveguide using high temperature superconductors. Therein, a cylindrical cavity with an input and an output is provided with an inner wall composed of superconductive material. In one strip line structure a low-loss dielectric is enclosed within a cavity with a superconductive wall and a superconductive strip mounted on a low-loss dielectric material overlying a superconducting ground plane or a conventional ground plane. The structure is substantially different than anything disclosed in the present application.

In addition to the foregoing, it is believed that a number of concerns are developing waveguide cavities in which HTS materials line the waveguide cavities or the waveguide cavities are constructed entirely of HTS. While considerable reduction in size is possible with this technology, the size of filters constructed in accordance with such a method is excessively large. Moreover, current technology does not allow the deposition as HTS thin films on any suitable cavity material. As a result, current cavities are typically made for bulk material which is typically only somewhat better than copper at best. Therefore, applications are expected to be limited to those areas where loses are very costly in small size is not desirable to the operating environment.

It has been known to make use of high-dielectric constant ceramics as resonators within waveguide cavities to allow size reduction of the resonator cavities. Placement of dielectric resonators within a waveguide cavity has in the past required that the resonator be supported at or near the center of the cavity or at least between the side walls of the cavity, which militates against substantial size reduction of the cavity. It is worthwhile to explore structures which would allow still further size reduction.

SUMMARY OF THE INVENTION

According to the invention, there is provided a waveguide cavity filter having a conductive housing, a plurality of high dielectric constant ceramic resonators disposed within the conductive housing and at least a portion of a sheet of superconductive material which is constrained to be at an ambient temperature below the critical temperature of the superconductor and disposed in contact with at least one of the side walls of the conductive housing and with an opposing surface of each of the resonators, such that the resonators are in close superconductive contact with the side walls of the conductive housing. In particularly, the superconductive sheet is a layer of high temperature superconductor. In a first embodiment of the invention, the resonators in the shape of cylindrical plugs are disposed with a flat surface juxtaposed to the side wall. In a second embodiment, the resonators are in the form of half cylindrical plugs with the axis of the half cylinder transverse to the axis of the resonator, in contact with the superconductor sheet and in juxtaposition to the side wall. In a further embodiment of the invention, the resonators are quarter circular cylindrical plugs and each of the flat side surfaces is in contact with a juxtaposed side wall of the conductive housing through a sheet of superconductive material.

The invention will be better understood by reference to following detail description in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a prospective view in partial cutaway of a hybrid resonator/filter in accordance with the invention.

Fig. 2 is a top cross-sectional view of a hybrid resonator/filter in accordance with the invention.

Fig. 3 is a side cross-sectional view of an alternative embodiment of a hybrid resonator/filter in accordance with the invention.

Fig. 4 is an end cross-sectional view of one embodiment of the invention.

Fig. 5 is an end cross-sectional view of a further embodiment of the invention.

Fig. 6 is an end cross-sectional view of a still further embodiment of the invention.

Fig. 7 is an end cross-sectional view of the embodiment of Fig. 3.

Fig. 8 is an end cross sectional view of a still further embodiment of the invention.

Fig. 9 is a prospective view in partial cutaway of a still further embodiment of the invention.

DESCRIPTION OF SPECIFIC EMBODIMENTS

Referring to Fig. 1, there shown a hybrid dielectric resonator/filter 10 according to one embodiment showing specific elements which are common to all embodiments described hereinafter. The filter 10 includes a rectangular cross-section conductive housing 12 and a plurality of high dielectric constant ceramic resonators 14 disposed within the housing which in this embodiment are right circular cylinders, or simply plugs 14. The ceramic plugs 14 are, according to the invention, mounted within the housing 12 with at least one surface 16 abutting a relatively thin layer 18 of superconducting material which in turn abuts an inner surface 20 of a conductive wall of the conductive housing 12. The layer 18 need not cover the entire wall surface 20. It may be as small as the surface area of surface 16.

A particular advantage of the invention is that the superconductive material minimizes losses within the cavity 22 formed by the housing 12 and allows construction of a hybrid resonator/filter of compact size relative to other structures of comparable performance characteristics. Whereas it would be necessary to space the resonator 14 from the conductive wall 20, the interposition of a superconductive layer 18 allows the resonator 14 to be juxtaposed to the wall 20, thereby reducing cavity height requirements.

The resonator 14 is preferably constructed a high performance ceramic such as zirconium stannate ($ZrSnTiO_4$) or advanced perovskite added material ($BaniTaO_3BaZrZnTaO_3$). Zirconium stannate provides acceptable performance above about 6 GHz and very good results at frequencies below 2 GHz. Perovskite added material is more suited for higher frequencies and is excellent above 4 GHz, although it is about 50% heavier.

The superconductive layer 18 is preferably constructed of the new class of high temperature superconductors, such as the ceramic yttrium-barium copper oxide, which is capable of superconducting at temperatures as high as about 77°K thus making it possible to be cooled by liquid nitrogen rather than more expensive and less readily available coolants such as liquid helium. The filter 10 according to the invention may therefore be provided with any suitable heat exchanger 24 for the coolant whereby the structure is cooled. The heat exchanger 24, which may well be part of an enclosing envelope, is used to maintain the housing 12 at or below the critical temperature (T_c) of the superconductor. The design of the heat exchanger 24 is a function of the environment. For example, in the context of a spacecraft, a premium is placed on size and weight, while cost is a secondary consideration.

The resonator 14 is preferably held in place mechanically by a spacer sheet or web 26. While it may be possible to provide an adhesive between the resonator 14 and the layer 18 at the abutting surface 16, it is preferred that the contact be made as free of contaminating materials as is possible.

As is conventional for a filter, there is an input port 28 and an output port 30 for coupling microwave energy through the structure. Other conventional elements, such as coupling probes 32 and 34 (Fig. 2) are also included.

Figs. 2 through 9 illustrate specific embodiments. Similar elements are referenced by identical enumeration. In Fig. 2, right circular cylindrical plugs mounted in a preselected pattern in the housing 12 form the resonators. They are disposed on the layer 18 of superconductive material substantially covering one wall of the housing 12. The input port 28 and output port 30 are provided with probes 32 and 34 which are impedance matched for coupling into the cavity 22. The placement and size of the resonators 14 are selected in accordance with generally understood design principles. A suitable reference for the design principles for the resonant modes in a shielded dielectric rod resonator is the paper by

Kobayashi et al. entitled "Resonant Modes for a Shielded Dielectric Rod Resonator" Electronics and Communications in Japan, Vol. 64-B, No. 11, 1981, pps. 44-51 (ISSN 0424-8368/81/0011/0044$7.50/0). This paper is attached hereto as an appendix. The designs herein are principally in support of the TE_{01X} modes of a rectangular resonant cavity. Where the cavity is provided with an additional superconductive structure therein, insertion loss is increased, conductivity is enhanced, and the size can be reduced relative to a comparable filter which does not benefit from the extremely low loss characteristics of a superconductor.

Referring to Fig. 3, there is shown an embodiment wherein resonators 14' are formed of half circular cylinders having the principal axis transverse to the axis of the rectangular resonator cavity 22. Superconductive layers 18 are disposed as pads between the faces 16 of the resonators 14' and the inner wall 20 of the housing 12.

Referring to Fig. 4, there is shown an end cross-sectional view of a filter 10, corresponding to either Fig. 1 or Fig. 2, wherein a first superconductive layer 18 underlies a resonator 14 and a second superconductive layer 19 is a sheet which overlays the resonator 14 and is in contact therewith. The layer 19 may extend the width and potentially the length of the cavity 22 to promote superconductive coupling to the cavity walls. In the alternative, a single layer 18 on one wall of the cavity 22 may be in contact with a right circular cylindrical plug 14 (Fig. 5). As a further alternative, layer 18 may be in contact with the right circular cylindrical plug 14 and second layer 19 may be spaced from the plug 14 and in contact with opposing wall 25 of the cavity 22.

In Fig. 7, a half cylinder resonator 14' as in Fig. 3 is in contact with a superconductive layer 18. The half cut dielectric resonator filter as shown in Fig. 3 and Fig. 7 has the advantage of allowing that only one face be in contact with HTS material, thereby reducing size and cost at the expense of somewhat reduced Q factor.

In Fig. 8, a configuration is illustrated wherein a quarter cylinder resonator 14" is disposed against superconductive layers 18 abutting two adjacent surfaces of the cavity 22, namely, a sidewall 27 and base wall 20. The quarter-cut dielectric resonator/filter in Fig. 8 offers the additional advantage of even smaller volume but at somewhat further reduced Q factor. A specific advantage of a quarter-cut design is the effective elimination of spurious HE modes of oscillation.

Referring to Fig. 9, there is shown a hybrid resonator/filter 10' suitable to support a different resonant mode, namely, the TE_{11} mode of oscillation. Plug-type resonators 14 are mounted on opposing end walls 36, 38 of a right circular cylindrical cavity 40, and each of the resonators 14 is mounted on a superconductive layer 18 against the adjacent end wall 36, 38. A coupling aperture 42 is provided for coupling between first and second cavity segments 44, 46. Input and output ports 28 and 30 are provided. This cavity design is similar to the type disclosed in U.S. Patent No. 4,540,955 issued September 10, 1985 to one of the co-inventors herein. The filter design in Fig. 9 is a HTS/dielectric resonator hybrid design which resonates at the HE_{111} mode with two orthogonal modes per cavity.

It is significant to note that high-temperature superconductor layers 18 are required only directly between the resonators 14 and the cavity walls 36, 38. Additional features are the exceptionally high Q factor, due in large part to the high temperature superconductors and low dielectric loss in the resonators at low temperature. The size of the resonators may be smaller when operating in a known cool ambient environment due to the effective increase in the dielectric constant of the ceramics. Operating the filter with resonators at reduced temperature improves efficiency of the resonators. Further, because a cooling system is needed which typically requires temperature regulation to maintain superconductivity, a filter according to the invention benefits from excellent temperature stability. The device is designed so that it can be tuneable.

The invention has now been explained with reference to specific embodiments. Other embodiments will be apparent to those ordinarily skilled in the art. It is therefore not intended that this invention be limited except as indicated by the appended claims.

WHAT IS CLAIMED IS:

1. A waveguide cavity resonator/filter having a conductive housing having interior walls and at least one high dielectric constant ceramic resonator element disposed within the conductive housing, further comprising:

at least a first superconductive sheet of superconductive material which is constrained to be at an ambient temperature below the critical temperature from superconduction, said sheet being disposed in contact with a first interior wall of the conductive housing and with an opposing flat surface of said resonator element, the superconductive sheet being sufficient to cover the flat surface, such that the resonator element is in superconductive contact with the first interior wall.

2. The resonator/filter according to claim 1, wherein the superconductive material is a high temperature superconductor.

3. The resonator/filter according to claim 1, wherein the cavity is formed of flat side walls with a rectangular cross section, wherein each resonator element is in the shape of a right circular cylindrical plug, and wherein the cylindrical plug is disposed with one flat surface abutting the superconductive sheet and juxtaposed to the first interior wall.

4. The resonator/filter according to claim 1, wherein the cavity is formed of flat side walls with a rectangular cross section, wherein each resonator element is in the shape of a half-cut circular cylindrical plug with a rectangular face, and wherein the half-cut cylindrical plug is disposed with the axis of the plug transverse to the axis of the cavity and the rectangular face abutting the superconductive sheet and juxtaposed to the first interior wall.

5. The resonator/filter according to claim 1, wherein the cavity is formed of flat side walls with a rectangular cross section, wherein the resonator element is in the shape of a quarter-cut circular cylindrical plug having two rectangular faces, and wherein the plug is disposed with the axis of the plug parallel to the axis of the cavity and the two rectangular faces abutting superconductive sheets and juxtaposed to adjacent side interior walls.

6. The resonator/filter according to claim 1, further including a second superconductive sheet extending across the cavity, wherein the cavity is formed of flat side walls with a rectangular cross section, wherein each resonator element is in the shape of a right circular cylindrical plug, and wherein the cylindrical plug is disposed with a first flat surface abutting the first superconductive sheet and juxtaposed to the first interior wall and disposed with a second opposing flat surface abutting the second superconductive sheet.

7. The resonator/filter according to claim 1, further including a second superconductive sheet extending across the cavity, wherein the cavity is formed of flat side walls with a rectangular cross section, wherein each resonator element is in the shape of a right circular cylindrical plug, wherein the cylindrical plug is disposed with a first flat surface abutting the first superconductive sheet and juxtaposed to the first interior wall and wherein the second superconductive sheet is juxtaposed to a second interior wall opposing said first interior wall.

8. A waveguide cavity resonator/filter having a cylindrical conductive housing having flat interior end walls and at least a first high dielectric constant ceramic resonator element disposed within the conductive housing, further comprising:

a first superconductive sheet of superconductive material which is constrained to be at an ambient temperature below the critical temperature from superconduction, said first sheet being disposed in contact with a first interior end wall of the conductive housing and with an opposing flat surface of the first resonator element, the superconductive sheet being sufficient to cover the flat surface, such that the first resonator element is in superconductive contact with the first interior wall.

9. The resonator/filter according to claim 1, further comprising:

a coupling aperture separating said housing into a first half cavity and a second half cavity, wherein said first resonator in the first half cavity; and

a second superconductive sheet of superconductive material which is constrained to be at an ambient temperature below the critical temperature from superconduction, said second sheet being disposed in contact with a second interior end wall of the conductive housing and with an opposing flat surface of said resonator element in the second half cavity, the second superconductive sheet being sufficient to cover the flat surface, such that the second resonator element is in superconductive contact with the second interior wall.

Attorney Docket No. 14586-28/91-2

HYBRID DIELECTRIC RESONATOR/ HIGH TEMPERATURE SUPERCONDUCTOR FILTER

ABSTRACT OF THE DISCLOSURE

A waveguide cavity filter having a conductive housing, a plurality of high dielectric constant ceramic resonators disposed within the conductive housing and at least a portion of a sheet of superconductive material which is constrained to be at an ambient temperature below the critical temperature of the superconductor and disposed in contact with at least one of the side walls of the conductive housing and with an opposing surface of each of the resonators, such that the resonators are in close superconductive contact with the side walls of the conductive housing. In particularly, the superconductive sheet is a layer of high temperature superconductor. In a first embodiment of the invention, the resonators in the shape of cylindrical plugs are disposed with a flat surface juxtaposed to the side wall. In a second embodiment, the resonators are in the form of half cylindrical plugs with the axis of the half cylinder transverse to the axis of the resonator, in contact with the superconductor sheet and in juxtaposition to the side wall. In a further embodiment of the invention, the resonators are quarter circular cylindrical plugs and each of the flat side surfaces is in contact with a juxtaposed side wall of the conductive housing through a sheet of superconductive material.

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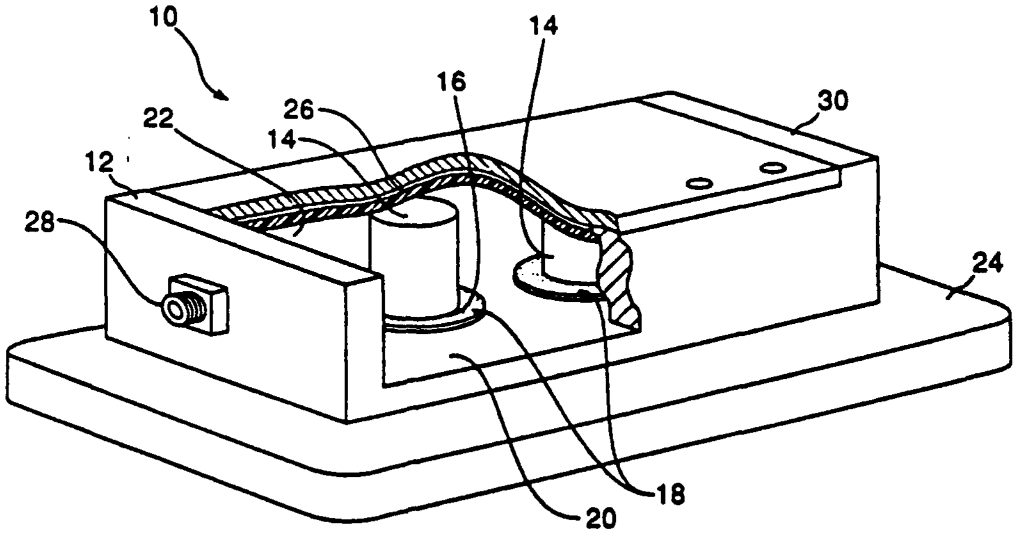


FIG. 1

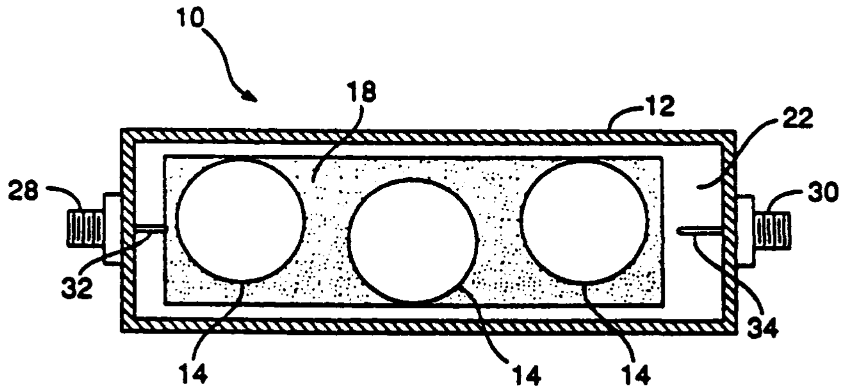


FIG. 2

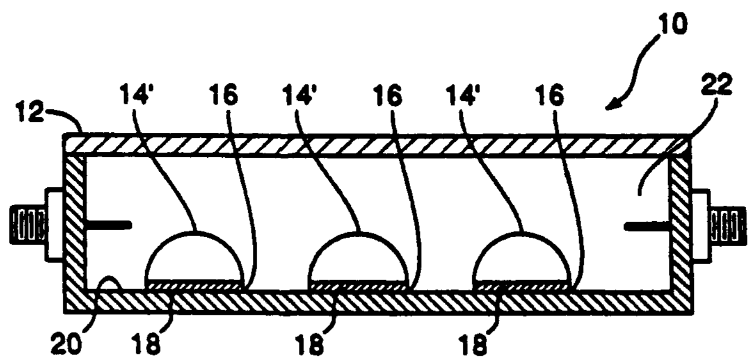


FIG. 3

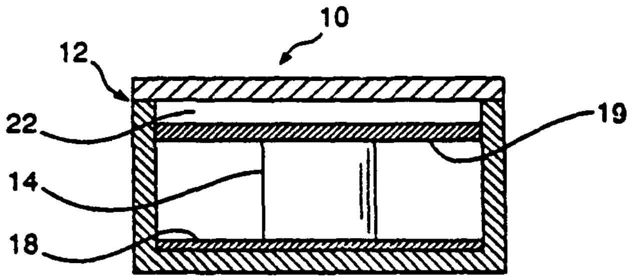


FIG. 4

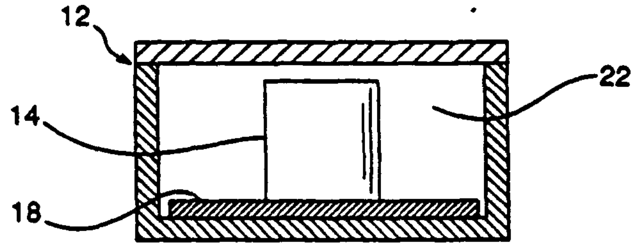


FIG. 5

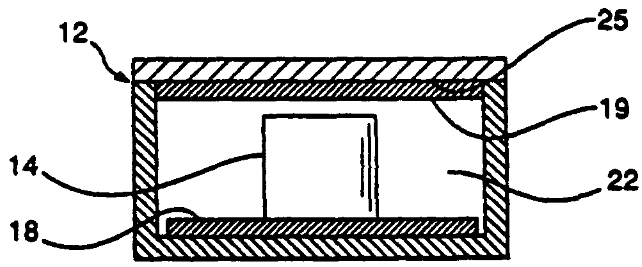


FIG. 6

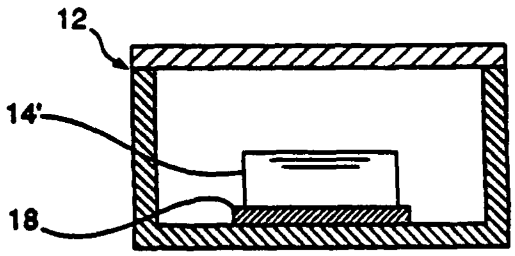


FIG. 7

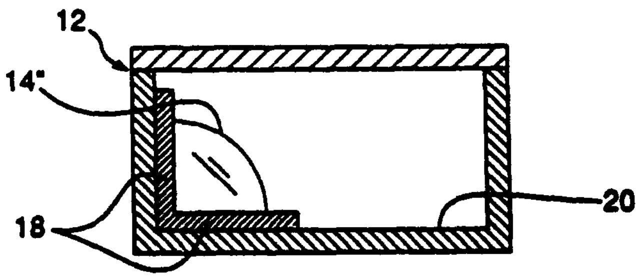


FIG. 8

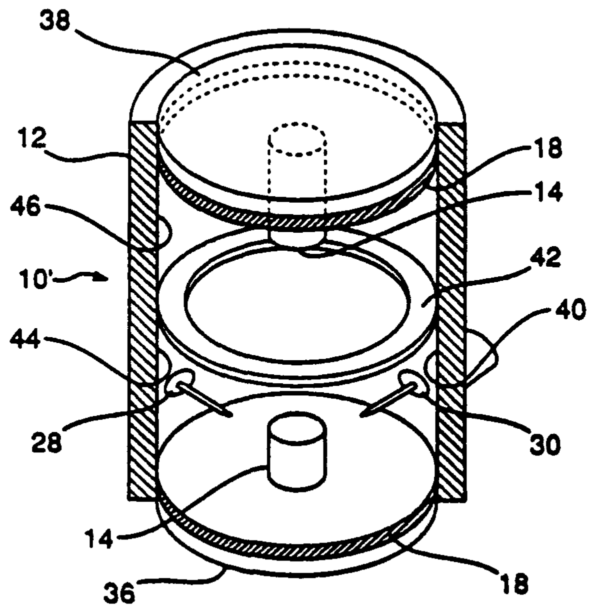
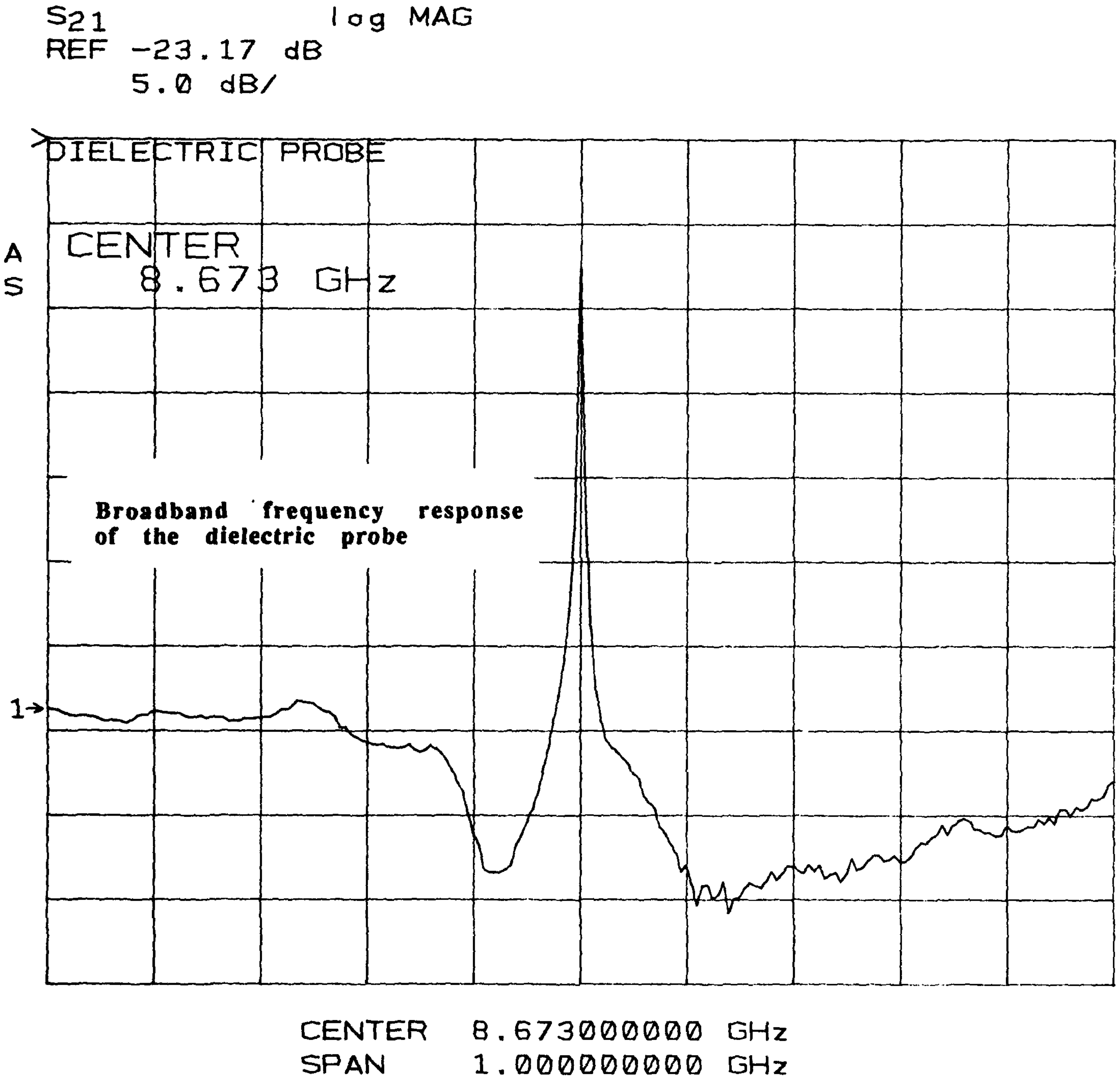


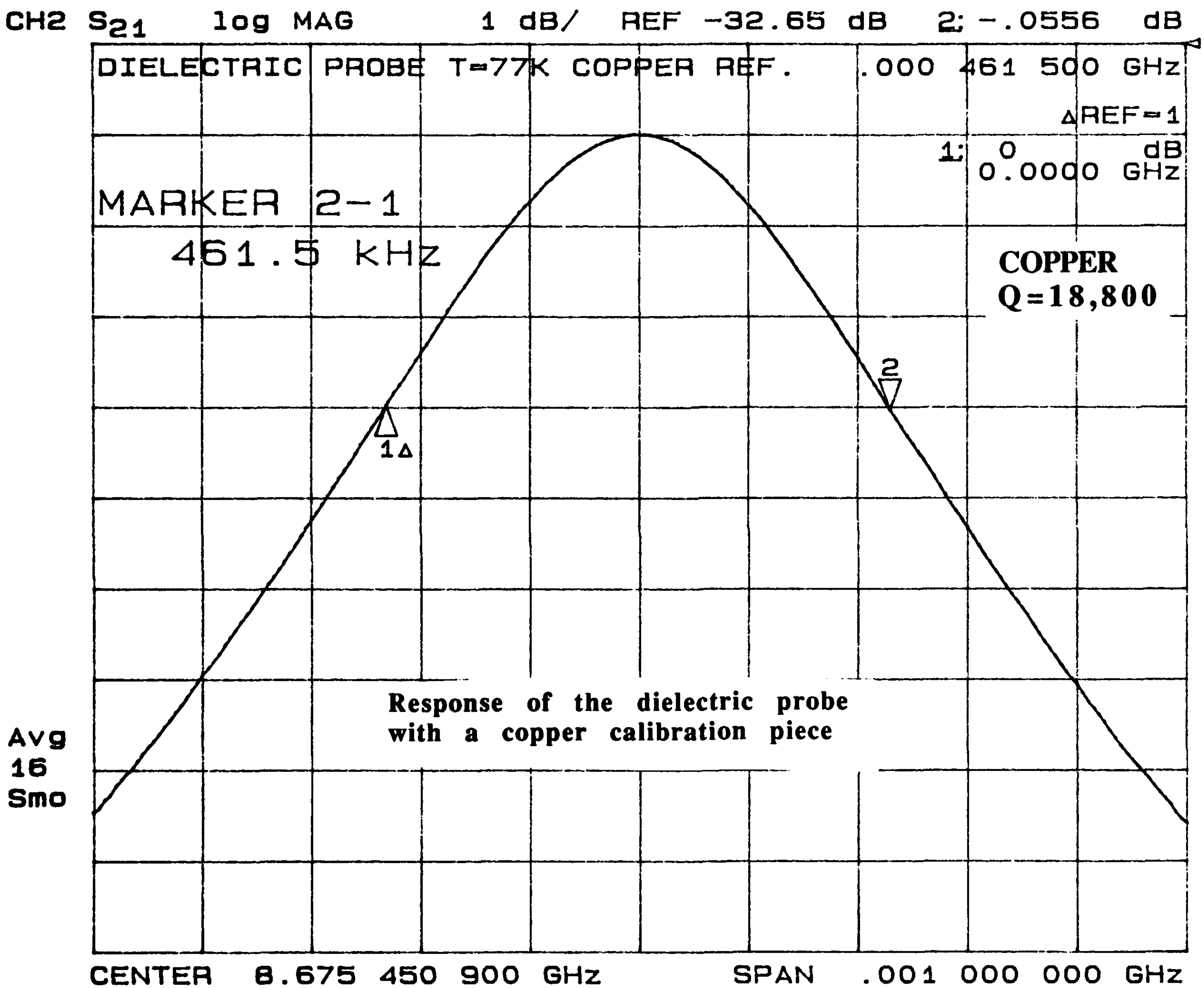
FIG. 9

APPENDIX G

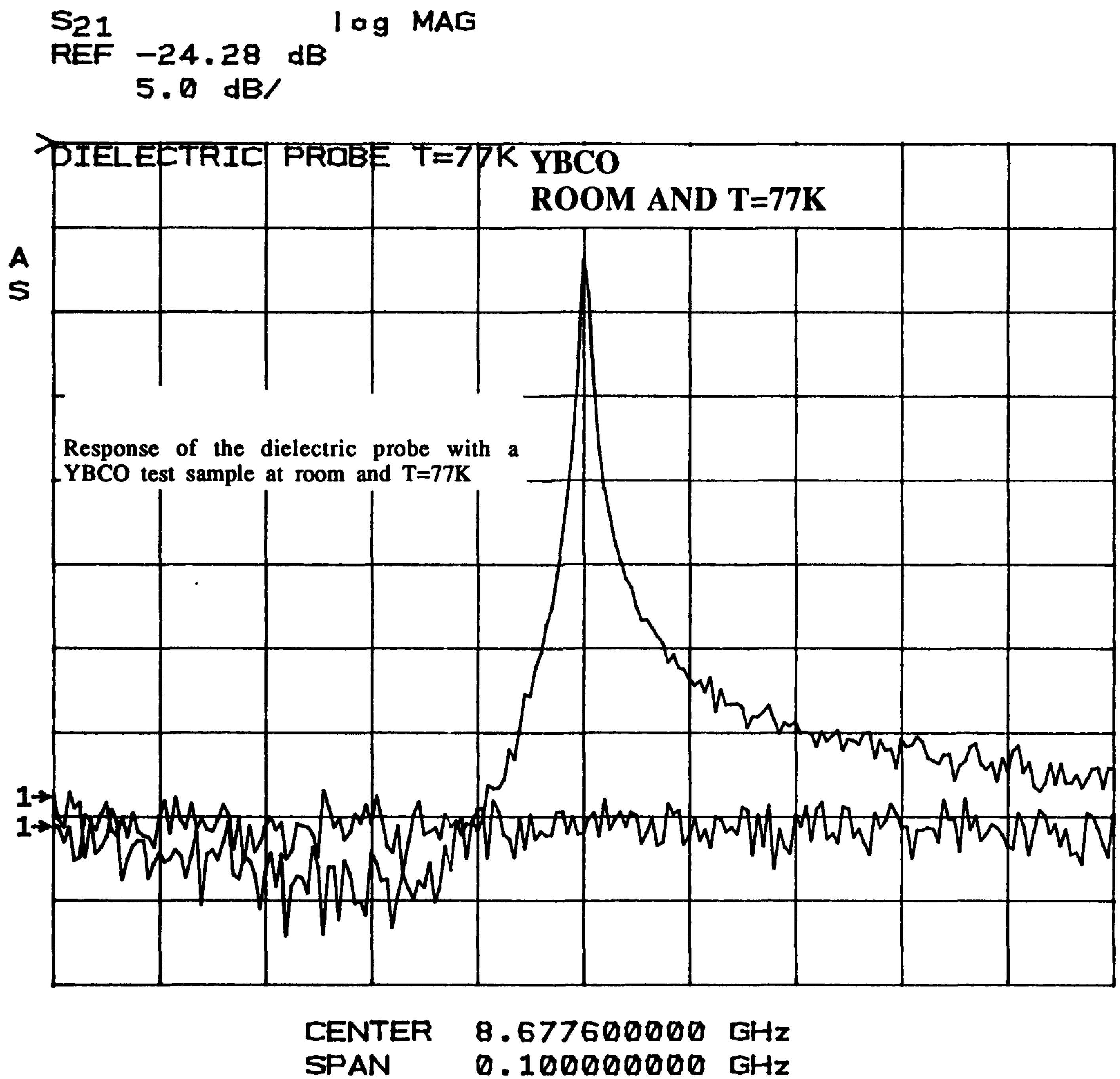
DIELECTRIC RESONATOR PROBE MEASUREMENT RESULTS FOR THE HTS FILMS USED FOR HTSSE



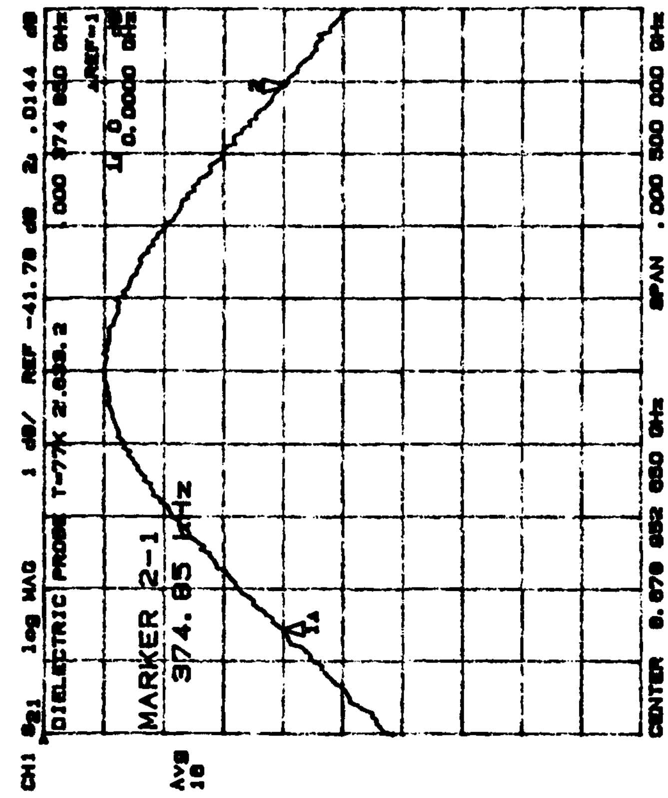
Broadband frequency response of the dielectric probe



Response of the dielectric probe with a copper calibration piece



Response of the dielectric probe with a YBCO test sample at room and T=77K


CH1 S21 log MAG 1 dB/ REF -41.78 dB
DIELECTRIC PROBE
MARKER 2-1
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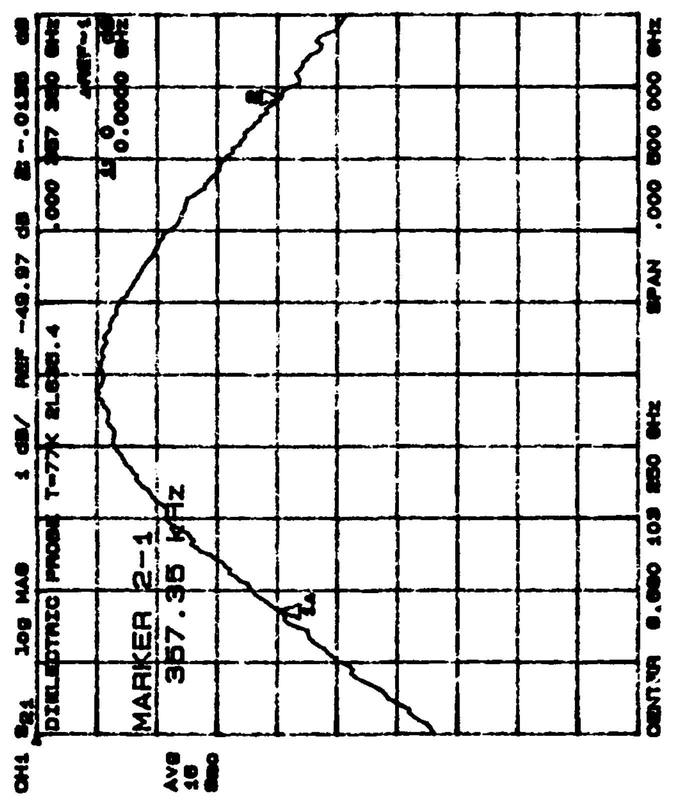
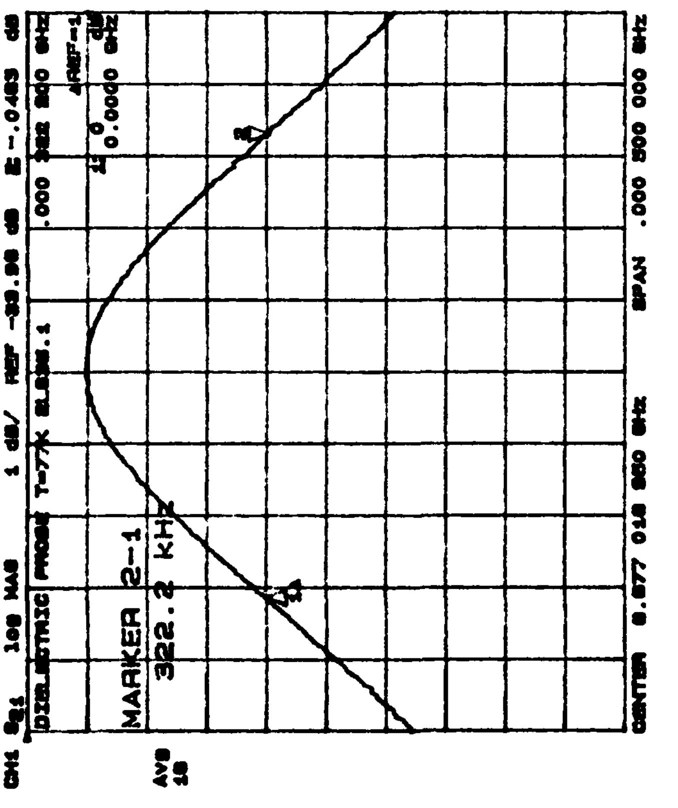
SPAN .000 500 000 GHz
Avg 16


CH1 S21 log MAG 1 dB/ REF -40.97 dB
DIELECTRIC PROBE
MARKER 2-1
357.35 kHz
SPAN .000 500 000 GHz
Avg 16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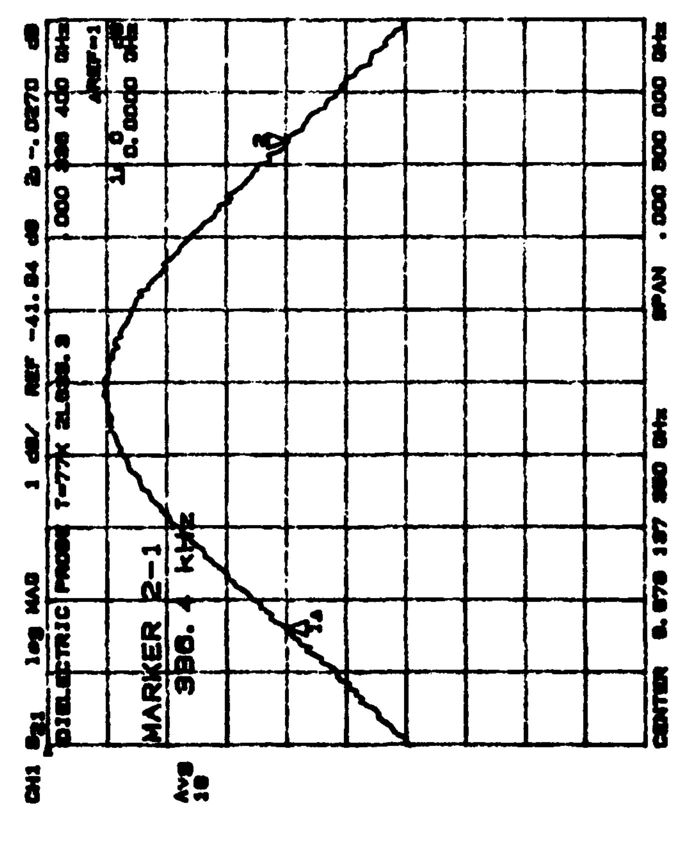
DIELECTRIC PROBE
MARKER 2-1
322.2 kHz
SPAN .000 500 000 GHz
Avg 16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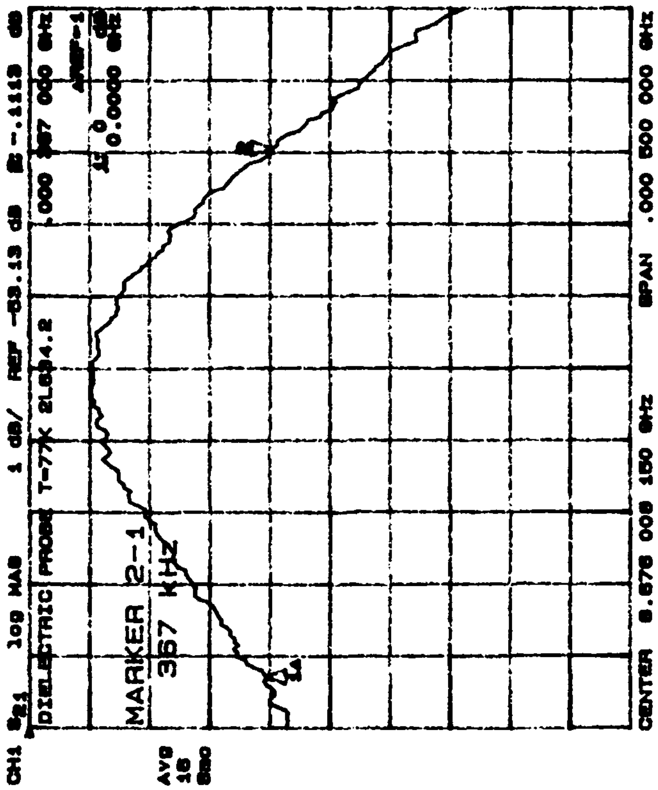
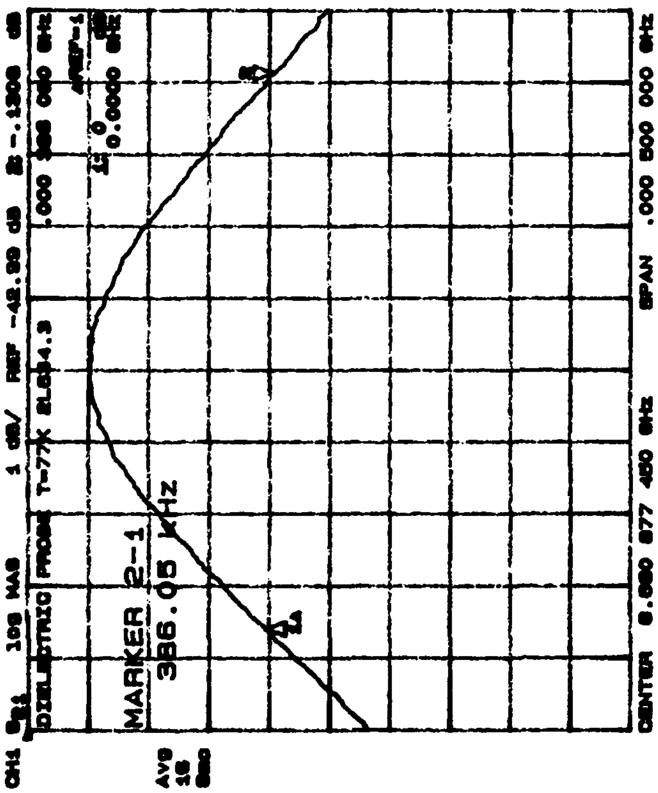
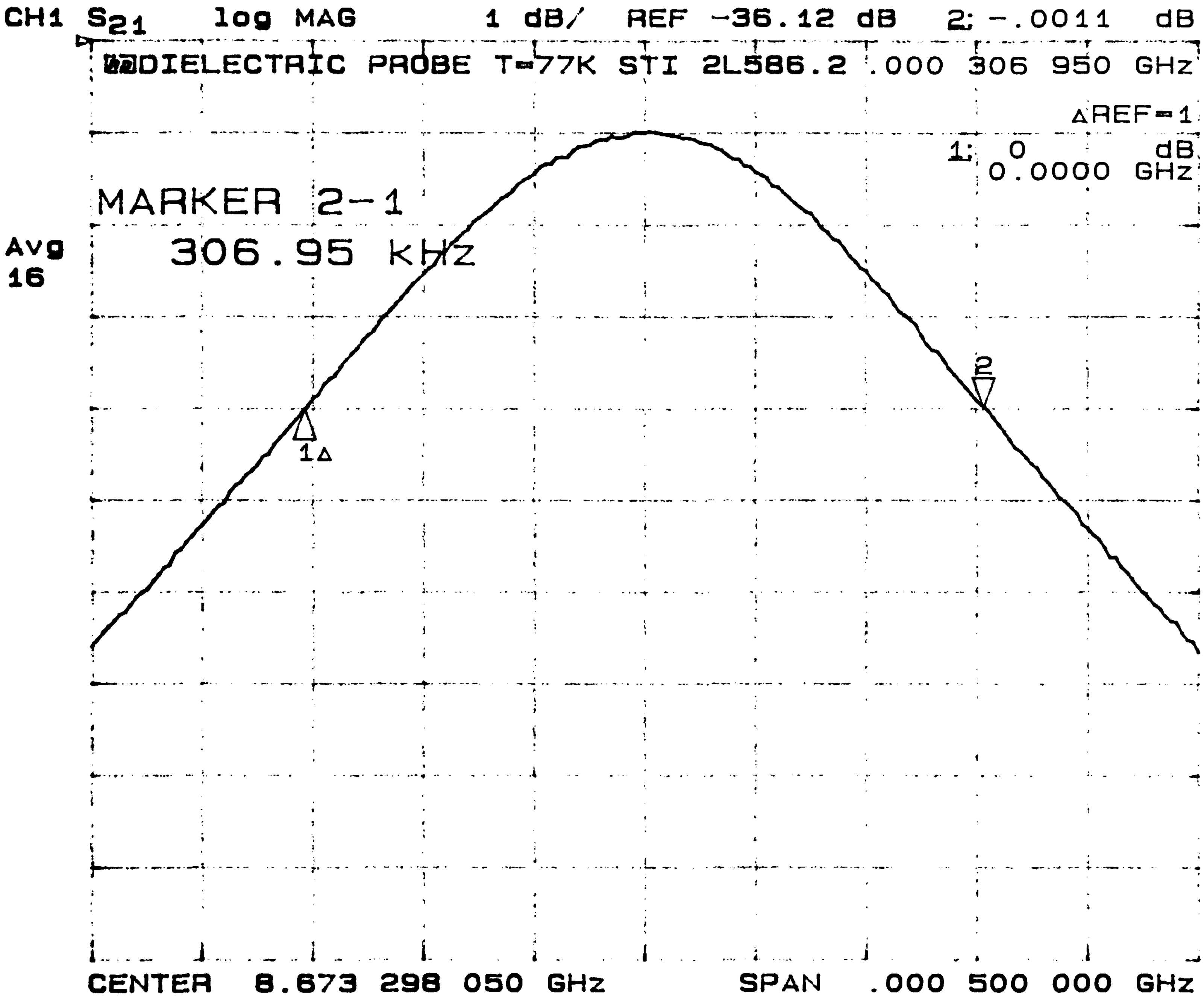
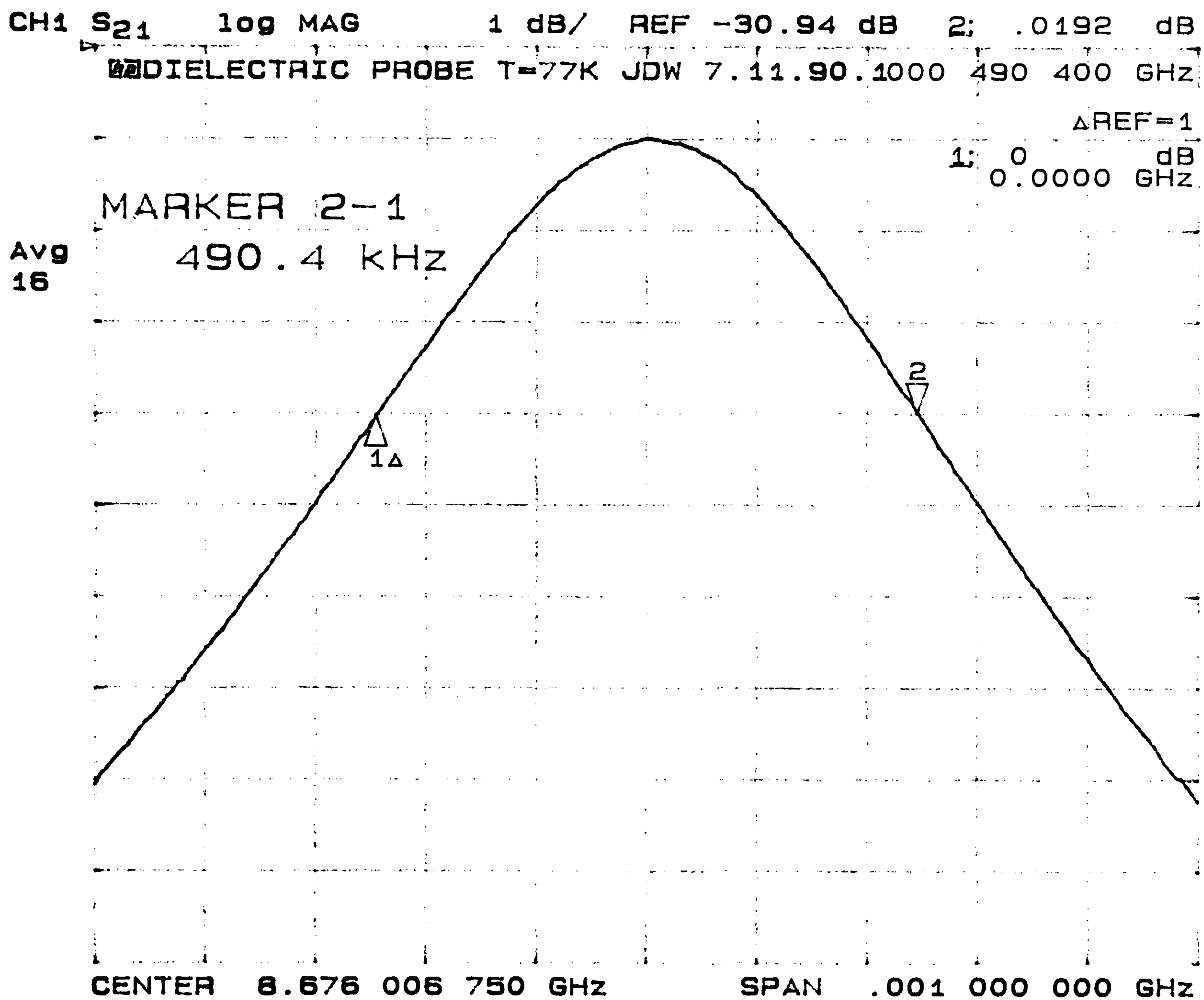
DIELECTRIC PROBE
MARKER 2-1
336.4 kHz
SPAN .000 500 000 GHz
Avg 16


MARKER 2-1
357 KHz

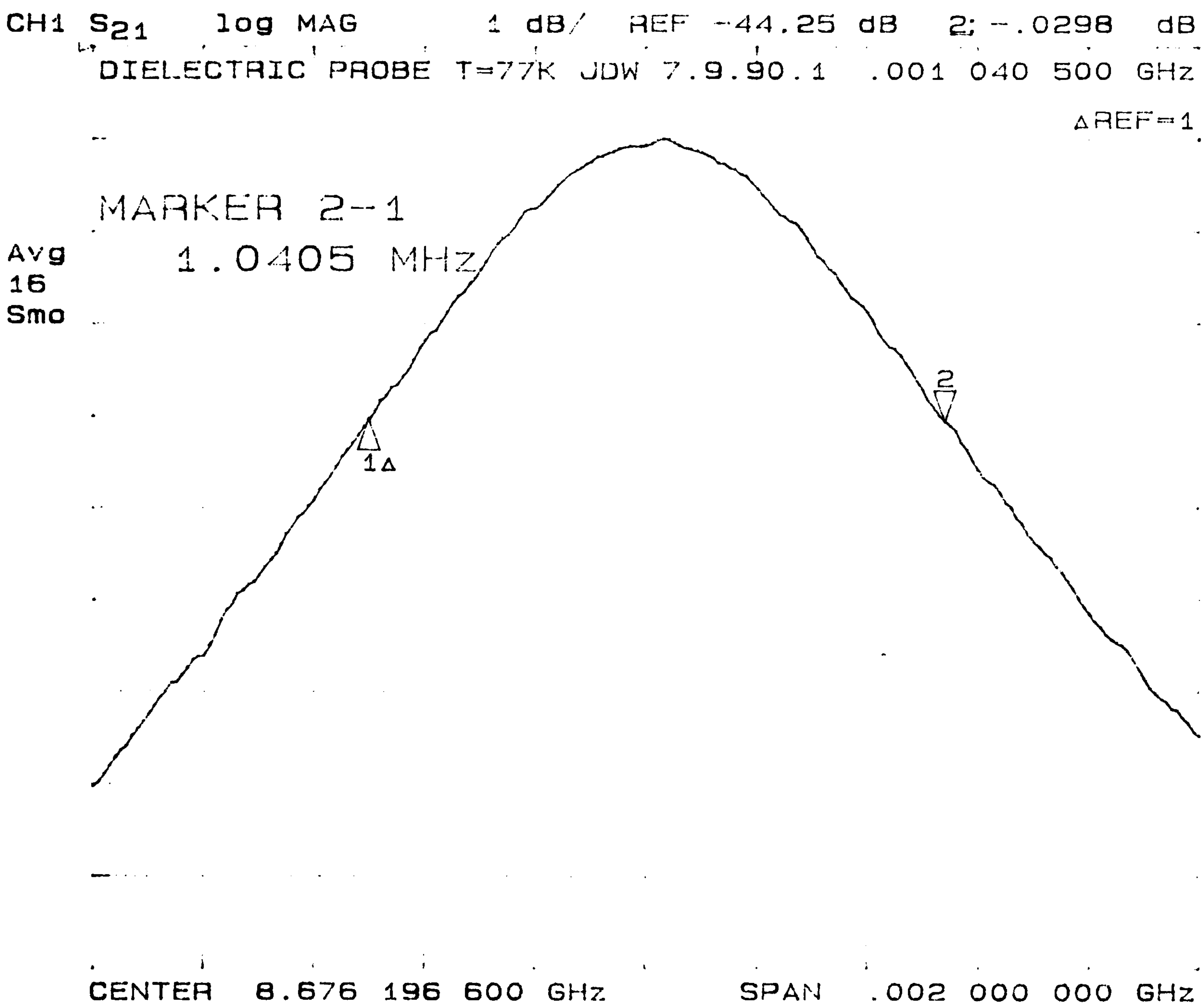

MARKER 2-1
386.05 KHz

Q=28,256

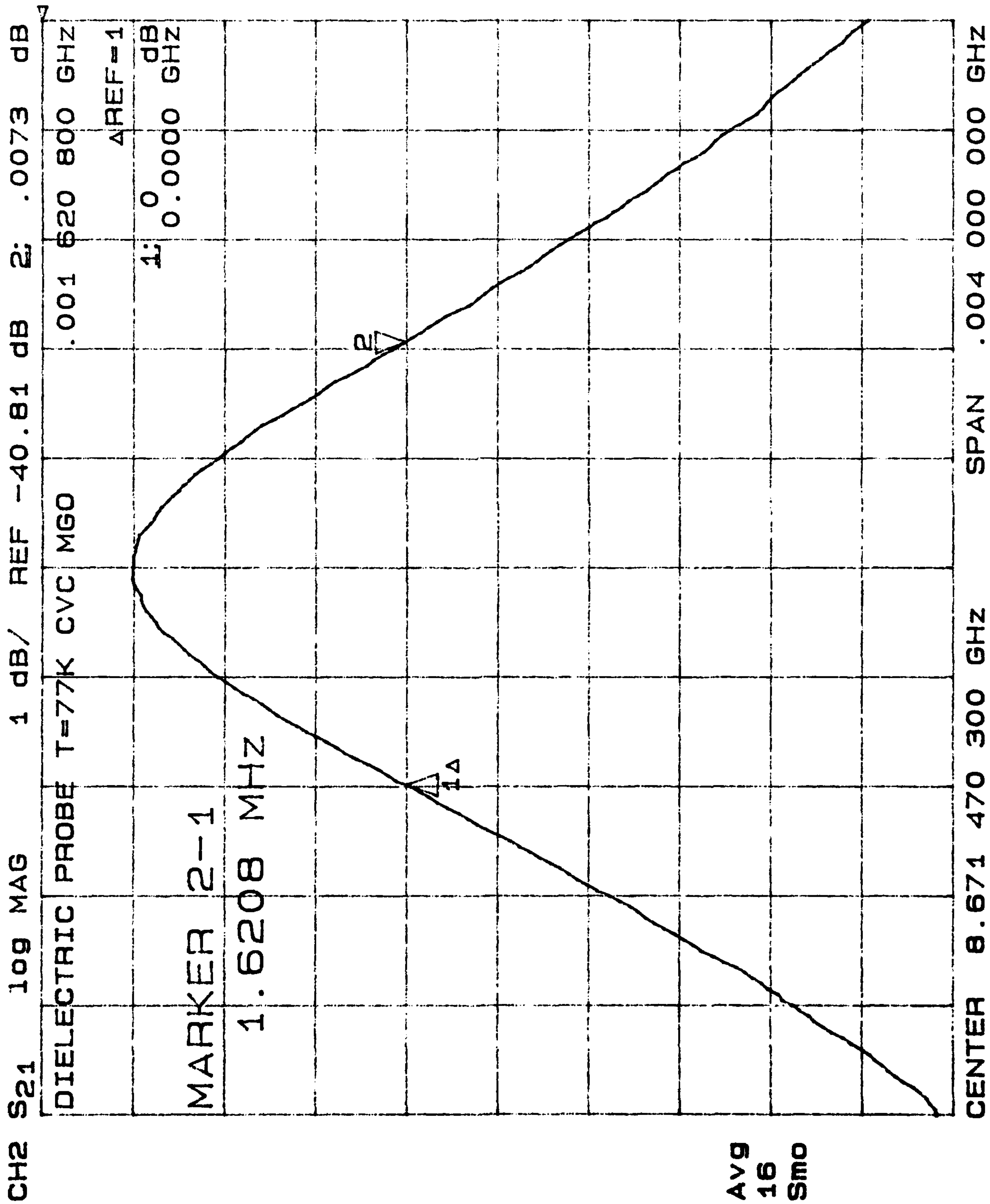

CH1 S21 log MAG 1 dB/ REF -36.12 dB 2: -.0011 dB
DIELECTRIC PROBE T=77K STI 2L586.2 .000 306 950 GHz
ΔREF=1
1: 0 dB
0.0000 GHz
MARKER 2-1
306.95 kHz
Avg
16
1Δ
2
CENTER 8.673 298 050 GHz SPAN .000 500 000 GHz



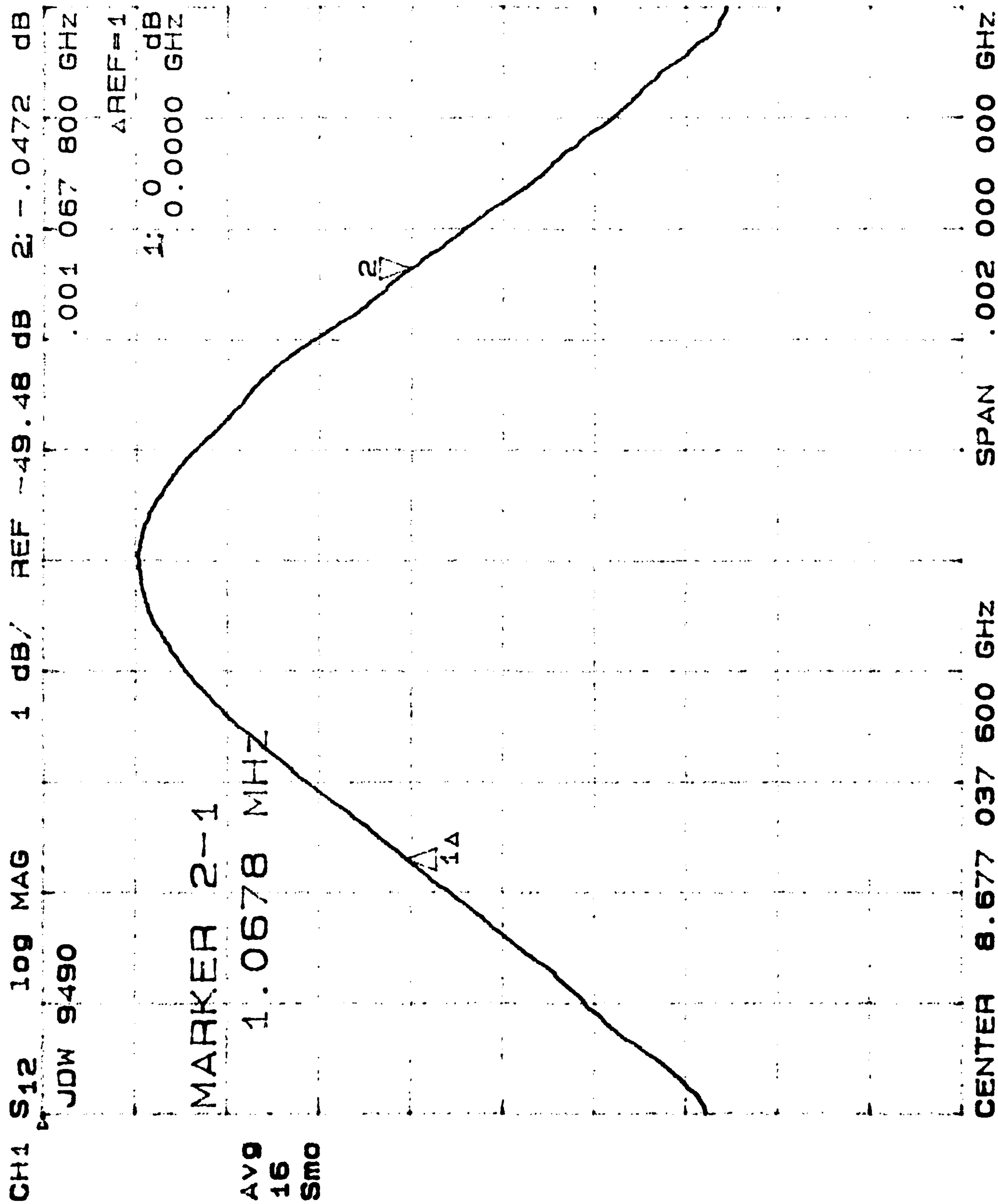
CH1 S21 log MAG 1 dB/ REF -30.94 dB 2; .0192 dB
DIELECTRIC PROBE T=77K JDW 7.11.90 .1000 490 400 GHz
ΔREF=1
1; 0 dB
0.0000 GHz
MARKER 2-1
490.4 kHz
Avg
16
2
1Δ
CENTER 8.676 006 750 GHz
SPAN .001 000 000 GHz



CH1 S21 log MAG 1 dB/ REF -44.25 dB 2; -.0298 dB
DIELECTRIC PROBE T=77K JDW 7.9.90.1 .001 040 500 GHz
ΔREF=1
MARKER 2-1
1.0405 MHz
Avg
16
Smo
1Δ
2
CENTER 8.676 196 600 GHz
SPAN .002 000 000 GHz



CH2 S21 log MAG 1 dB/ REF -40.81 dB 2: .0073 dB
DIELECTRIC PROBE T=77K CVC MGO
.001 620 800 GHz
ΔREF=1
1: 0 dB
0.0000 GHz
MARKER 2-1
1.6208 MHz
Avg
16
Smo
CENTER 8.671 470 300 GHz SPAN .004 000 000 GHz


CH1 S12 log MAG 1 dB/ REF -49.48 dB 2: -.0472 dB
JDW 9490
.001 067 800 GHz
ΔREF=1
1: 0 dB
0.0000 GHz
MARKER 2-1
1.0678 MHz
Avg
16
Smo
CENTER 8.677 037 600 GHz
SPAN .002 000 000 GHz